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On Dislocation Theory and the Physical Changes Produced by Plastic Deformation

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QUANTUM mechanical calculations[1] of the elastic constants of solids have been made by assuming that when an external stress is applied, the atoms of the crystal are displaced slightly from their equilibrium positions. It is assumed that these equilibrium positions form a perfectly periodic lattice. These calculations lead to the conclusion that Hooke's law should be valid up to stresses at least as large as 10^{10} dyne/cm^2. Experimentally, it is found that large deviations from Hooke's law occur for stresses of about 10^7 dyne/cm^2. Thus it appears that plastic deformation is to be associated with the behavior of some kind of crystalline imperfection in a solid under stress. In a recent series of articles, Seitz and Read[2] consider the various types of imperfections which have been used to discuss plastic deformation. They conclude that the use of *dislocations*[3] yields the most satisfactory description of plastic deformation given to date.

In the present article, we shall use dislocations to discuss the physical changes which take place in a solid when it is severely deformed at temperatures low enough so that resoftening does not take place. According to current theories, severe cold working creates many new imperfections and causes them to move through the solid. Suppose then a soft, well-annealed solid is severely deformed. The changes which occur in many of its physical properties can be attributed to the change in the density of dislocations. In this paper, we shall treat changes in the following properties: hardness, energy stored, magnetic properties, density and elastic constants, and the electric resistance.

Before we describe a dislocation it will be necessary to consider certain geometric features of the process of slip in a single crystal. If a single crystal is subjected to a small tensile stress, it will elongate according to Hooke's law. If the component of the shearing stress, acting along a definite crystallographic direction, exceeds a certain value the crystal will undergo considerable plastic deformation. For most crystals, this critical shearing stress is about 10^7 dyne/cm^2. The permanent deformation apparently takes place by a sliding of thin slices of the crystal over one another. The faces of the slices are usually those crystallographic planes in which the atoms are most closely packed. The direction of slip is the direction of the most closely packed line of atoms on the slip plane. A microscopic examination of

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[1] For a survey see Seitz, *The modern theory of solids* (McGraw-Hill, 1940), chap. X.

[2] Seitz and Read, J. App. Phys. **12**, 100, 170, 470, 538 (1941).

[3] Prandtl, Zeits. f. angew. Math. u. Mech. **8**, 85 (1928); Dehlinger, Ann. d. Physik **2**, 749 (1929); Orowan, Zeits. f. Physik **89**, 634 (1934); Polanyi, Zeits. f. Physik **89**, 660 (1934); Taylor, Proc. Roy. Soc. **145**, 362 (1934).

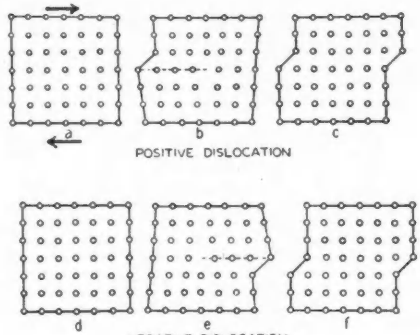

FIG. 1. Generation of dislocations in a mosaic block. In *a*, *b* and *c* a positive dislocation is generated at the left-hand side of the block and moves toward the right; in *d*, *e* and *f* a negative dislocation is formed and moves to the left. The arrows in *a* indicate the component of the external shearing stress that is responsible for the plastic deformation. [After G. I. Taylor.]

a single crystal which has been elongated by several percent shows clearly the step-like discontinuities produced at the surface when slip occurs. The slices, bounded by slip planes, are several microns thick at room temperatures.

DISLOCATION THEORY

In Fig. 1 we consider the formation and motion of a line dislocation.[4] The external forces which lead to the creation and motion of the dislocation act on the crystal in the manner indicated by the arrows in *a*. The atoms shown lie in a crystallographic plane that is normal to the slip plane. In *b* or *e* the axis of the dislocation is perpendicular to the plane of the figure. Thus parallel atomic planes above or below the plane of the drawing will have the same distribution of atoms about the axis of the dislocation. It is clear that, if either of the dislocations shown moves completely across the block, the material above the slip plane on which the dislocation moves will be shifted relative to the material below by a distance equal to the lattice constant of the material. Suppose that a positive and a negative dislocation exists upon the same slip plane. It is then evident from Fig. 1 that if they come together they will annihilate each other, thus leaving a perfect crystal.

We can now qualitatively show that the potential energy of a crystal containing a dislocation is larger than the potential energy of a perfect crystal. The potential energy associated with each atom is smallest when it is in a lattice position. Since the atoms near the axis of a dislocation are not in lattice positions, they will have more potential energy than they would have in a perfect crystal. It is found that the increase in energy of a thin crystalline slab, whose faces are perpendicular to the axis of the dislocation and whose thickness is the lattice constant of the material, is about 1 electron-volt. This energy of formation[5] is supplied by the external forces that produce the deformation. It can also be seen that a dislocation will tend to move towards the surface of a crystal. If the dislocation is far from the surface, the material around it is strained and possesses considerable strain energy. If the dislocation moves to the surface, the strains are gradually released and when the dislocation reaches the surface, as in *c* or *f* of Fig. 1, we are left with a perfect crystal.

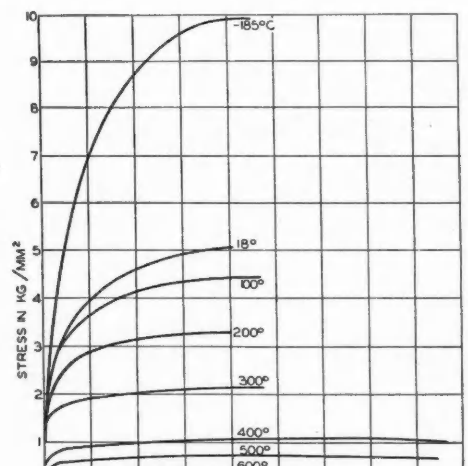

FIG. 2. Stress-strain curves for aluminum at various temperatures. All of these curves are parabolic, at least near the origin. [Boas and Schmid.]

[4] There is much evidence that most solids consist of a mosaic of blocks about 10^{-4} cm on a side; see the survey in the *Report of the international conference on physics, 1934* (Cambridge Univ. Press, 1935), vol. 2. According to Taylor, dislocations are formed in the regions between these mosaic blocks and move through them.

[5] Koehler, Phys. Rev. **60**, 405 (1941).

HARDNESS

The work hardening of a metal is clearly shown in the usual stress-strain diagram. Figures 2 and 3 are stress-strain curves for well-annealed single crystals of aluminum and cadmium.[6] Since it is found experimentally that the progress of plastic deformation in a single crystal is determined by the component of the shearing stress in the slip direction, we have used this component as the stress in Figs. 2, 3 and 4. For small stresses, up to a resolved shearing stress of about 10^7 dyne/cm^2, a crystal deforms elastically. If we gradually increase the resolved shearing stress above this value, the stress and strain will increase along the curve in Fig. 4 from point A to point B. If, at point B, we release the applied stress, the crystal will contract elastically along the line BC. The crystal has evidently suffered plastic deformation of amount OC. If we again gradually apply stress, the crystal will deform elastically along CB. If additional stress is then gradually applied, the crystal will deform plastically along the curve BD. Thus the stress-strain curve gives essentially the shearing stress required to produce plastic deformation as a function of the strain which has taken place.

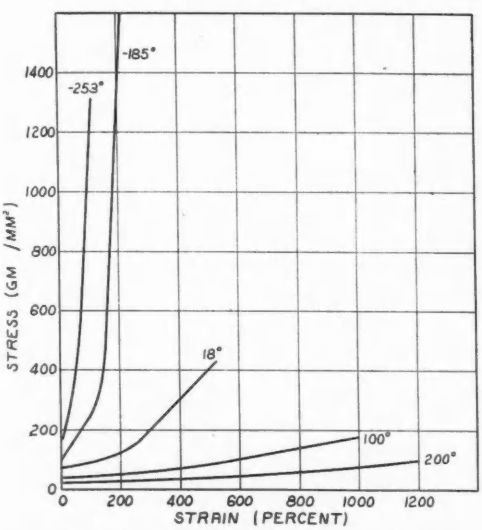

FIG. 3. Stress-strain curves for cadmium at various temperatures. [Boas and Schmid.]

[6] Boas and Schmid, Zeits. f. Physik **71**, 703 (1931); **61**, 767 (1930).

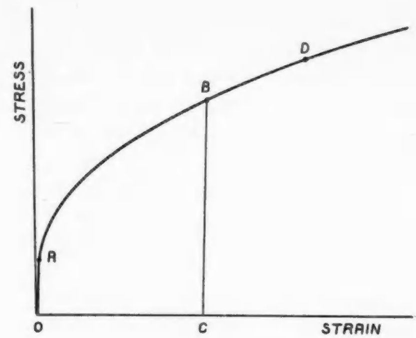

FIG. 4. The mechanical behavior of an initially annealed solid during plastic deformation.

An interpretation of *work hardening* on the basis of dislocation theory was first given by Taylor[3] who pointed out that dislocations exert forces on one another.[7] He found that like dislocations repel one another whereas unlike dislocations attract. Thus, as the deformation of an initially unstrained crystal proceeds, large numbers of dislocations become trapped in the interior of the crystal. (The forces acting between dislocations do not allow one dislocation to pass freely by another dislocation.) A larger external stress is then required to move dislocations through the crystal and the material has become work-hardened.

Let us use these ideas to obtain theoretically the form of the stress-strain curve. Consider two dislocations, one at the origin and one at the point (X, Y). We shall suppose that the axes of the dislocations extend in the Z direction and that the slip direction is parallel to the X axis. The component of force acting in the slip direction on the dislocation at (X, Y) is[8]

$$F_X = \pm\frac{mG\lambda^2}{2\pi(m-1)}\left[\frac{X}{X^2+Y^2} - \frac{2mXY^2}{(m-1)(X^2+Y^2)^2}\right], \quad (1)$$

where m is the reciprocal of Poisson's ratio, λ is

[7] The force between two dislocations is defined as the negative of the derivative of the potential energy of the crystal with respect to the distance between the dislocations.

[8] Taylor used only the first term of Eq. (1). Reasons for the introduction of the second term are given in reference 5.

the lattice constant of the material and G is its shear modulus. In Eq. (1) the positive (or negative) sign is used if we are considering two like (or unlike) dislocations. Consider a lattice of positive and negative dislocations such as is shown in Fig. 5. Unlike dislocations have not been put on the same slip plane because they would attract and annihilate one another. We wish to calculate the force acting on the positive dislocation located at (X_1, a). The force produced by the surrounding positive dislocations is zero because of symmetry. We shall assume that only the neighboring rows of negative dislocations are near enough to the positive dislocation at (X_1, a) to exert an appreciable force on it. The force on it is

$$f_X = -\frac{mG\lambda^2}{\pi(m-1)} \sum_{n=-\infty}^{+\infty} \left[\frac{(X_1-nb)}{(X_1-nb)^2+a^2} - \frac{2ma^2(X_1-nb)}{(m-1)(\{X_1-nb\}^2+a^2)^2} \right]. \quad (2)$$

On summing this series one obtains

$$f_X = -\frac{mG\lambda^2}{b(m-1)} \left[\frac{\sin\left(\frac{2\pi X_1}{b}\right)}{\cosh\left(\frac{2\pi a}{b}\right) - \cos\left(\frac{2\pi X_1}{b}\right)} \right] \times \left[1 - \frac{2\pi m a \sinh\left(\frac{2\pi a}{b}\right)}{b(m-1)\left\{\cosh\left(\frac{2\pi a}{b}\right) - \cos\left(\frac{2\pi X_1}{b}\right)\right\}} \right]. \quad (3)$$

The force which must be exerted on each positive dislocation to push the positive dislocation lattice through the negative dislocation lattice is obtained by locating the largest value of f_X. The largest value of f_X occurs when X_1 is approximately the negative of one-fourth of b. Thus the external shearing stress must produce the following force on each positive dislocation before further plastic deformation will take place:

$$f_{X\,\max} = \frac{2mG\lambda^2}{b(m-1)} \left[\frac{2\pi m}{(m-1)} - 1 \right] \exp(-2\pi a/b). \quad (4)$$

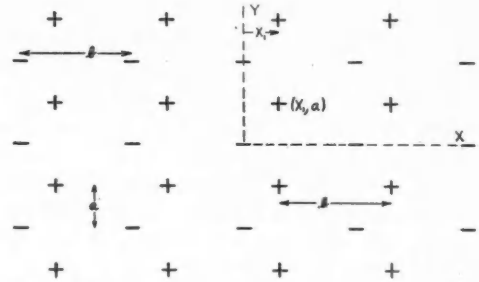

FIG. 5. An array of positive and negative dislocations produced during work hardening.

Expression (4) is an approximate formula which is valid in the region where $\cosh(2\pi a/b)$ is equal to $\sinh(2\pi a/b)$. The force produced on each positive dislocation by an external shearing stress τ_{XY} is

$$f_{X\,\text{ext}} = \frac{m\lambda}{\pi(m-1)} \tau_{XY}. \quad (5)$$

Thus the external shearing stress necessary to produce further plastic deformation is

$$\tau_{XY} = \frac{2\pi G\lambda}{b} \left[\frac{2\pi m}{(m-1)} - 1 \right] \exp(-2\pi a/b). \quad (6)$$

We must now determine the relation between a, b and the plastic strain that has taken place. Suppose the block through which the dislocations move is of length L in the slip direction. We shall take its dimensions along the Y and Z directions to be h. If a dislocation travels completely across the block, then the portion of the block above the slip plane of the dislocation will move a distance λ relative to the portion below the slip plane. If the dislocation moves $1/n$th of the way across, the top moves a distance λ/n relative to the bottom. We shall assume that all dislocations which enter the block are trapped. Then, on the average, the dislocations making up the lattice have traveled half way across the block and the average amount of slip per dislocation is $\frac{1}{2}\lambda$. The distance that the top of the block has moved relative to the bottom is therefore

$$s = \tfrac{1}{2}\lambda \text{ (No. of dislocations in block)} = \lambda Lh/2ab.$$

The plastic shearing strain which has taken place is

$$S = s/h = \lambda L/2ab. \quad (7)$$

Since both a and b cannot be determined from this equation, it is necessary to assume some relation between them. Taylor assumed that they are equal. Then

$$a=b=(\lambda L/2S)^{\frac{1}{2}} \tag{8}$$

and Eq. (6) becomes

$$\tau_{XY}=2\pi G\exp(-2\pi)\left(\frac{2\lambda}{L}\right)^{\frac{1}{2}}\left[\frac{2\pi m}{(m-1)}-1\right]\sqrt{S}. \tag{9}$$

Thus the resolved shearing stress, necessary to produce plastic deformation, is proportional to the square root of the shearing strain. It is clear that L must not be interpreted as an external linear dimension of a single crystal specimen because the observed stress-strain curve does not depend on the dimensions of the crystal employed. Taylor therefore assumes that L is the order of the length of a mosaic block. He supposes that dislocations originate in the disorganized region between two mosaic blocks. They then travel through several blocks and are eventually stopped at one of the regions between blocks. Since thermal agitation would help the dislocations through these difficult regions, we should expect L to increase with increasing temperature. Using these ideas, Taylor was able to predict stress-strain curves for single crystals of aluminum, rocksalt and gold over wide ranges of temperature. The type of agreement found is indicated in Fig. 6. The value of L found here does not differ essentially from that given by Taylor. At room temperature we find that the experimental and theoretical curves agree if $L=2.8\times10^{-4}$ cm in the case of aluminum. Taylor found $L=4.2\times10$ cm^{-4}. The value of L found for aluminum at very low temperatures agrees well with other measurements on the size of a mosaic block. The dimensions of the dislocation lattice in a highly worked aluminum crystal at room temperature are, according to Eq. (8), $a=b=2\times10^{-6}$ cm ($S=1.2$, $L=2.8\times10^{-4}$ cm).

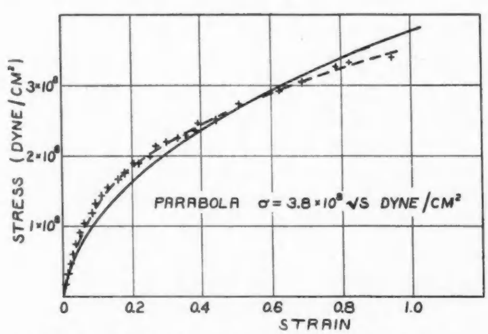

FIG. 6. Comparison of the observed stress-strain curve for aluminum with that predicted by Taylor's theory ($L=5.3\times10^{-4}$ cm).

Taylor's theory can also be used to obtain stress-strain curves of the type shown in Fig. 3. The fit between experimental and theoretical curves is achieved by assuming a value of L appropriate for the particular temperature used and then calculating a and b at each point along the curve from Eqs. (6) and (7). We do not know yet whether it is possible to arrange matters so that the stress-strain curve at different temperatures can be obtained from one another by varying L without changing the relations between a and b.

TABLE I. Values of the maximum energy (cal/gm) stored during work hardening.

Al	Cu	Fe	Ni	Brass
1.1	0.5	1.2	0.78	0.49

ENERGY STORED

It is found experimentally that the internal energy of a solid increases when the material is cold-worked. Starting with an annealed specimen, one finds that the stored energy varies approximately linearly with the strain over a considerable range of strain.[9] In the case of the face-centered cubic and the body-centered cubic metals, the stored energy eventually approaches a saturation value. The stress-strain curves of these metals exhibit a similar behavior, the stress approaching a constant value for large strains. The maximum increase in the energy content of these metals is of the order of 1 cal/gm. In Table I are listed experimental values[9] for the maximum increase in the stored energy in various materials. In the case of the metals forming hexagonal crystals—zinc, cadmium and tin—the stress-strain curves do not approach a constant value for large strains. It would be interesting to determine experimentally whether the energy stored in these metals approaches a saturation value.

[9] Taylor and Quinney, Proc. Roy. Soc. **143**, 307 (1934); **163**, 157 (1937).

TABLE II. Data used in calculations of the saturation energy.

	NaCl	Cu	Al	Ni	Fe
Slip direction	(110)	(110)	(110)	(110)	(111)
Shear modulus (10^{-11} dyne/cm^2)	1.872	4.53	2.665	7.69	8.114
Poisson's ratio	0.2053	0.340	0.343	0.309	0.280
r_0 (angstrom)	7.97	6.15	6.90	5.71	5.48
λ (angstrom)	3.979	2.552	2.855	2.480	2.478
Density (gm/cm^3)	2.165	8.93	2.699	8.80	7.865

TABLE III. Saturation energies per unit mass.

	Cu	Al	Ni	Fe
Spacing R, dislocation pairs	24.3	22.7	25.3	21.1
Spacing a, rectangular lattice	34.7	32.4	35.8	30.0
Spacing a, diagonal lattice	29.2	27.3	30.2	25.0
Energy stored (cal/gm), dislocation pairs	0.506	0.990	0.645	0.968
Energy stored (cal/gm), rectangular lattice	0.518	1.01	0.851	0.963
Energy stored (cal/gm), diagonal lattice	0.507	1.13	0.832	0.942
Energy stored (cal/gm), experimental	0.5	1.1	0.78	1.2

The first three rows list the separations of dislocations in work-hardened materials calculated by making the theoretical value for the energy stored equal to the experimental value. The spacings are given as multiples of λ, the shortest interatomic distance. The next three rows give theoretical values for the stored energy, calculated on the assumption that the dislocations are separated by 24λ in the case of the conglomeration of dislocation pairs, by 34λ in the case of the rectangular dislocation lattice and by 29λ in the case of the diagonal lattice of dislocations.

We have seen earlier that each dislocation has associated with it a certain stress field. According to dislocation theory, the energy stored in a cold-worked metal appears because of the presence of these internal stresses. In this section, we shall calculate the amount of strain energy associated with the large numbers of dislocations that appear in a highly worked metal.

Consider a positive and a negative dislocation which are separated by a distance R. If the stresses surrounding the dislocations are used to calculate the total strain energy W associated with this pair, one finds that

$$W=\frac{mG\lambda l}{2\pi(m-1)}\log\frac{R}{2r_0}+\frac{2lW_i}{\lambda}, \qquad (10)$$

where l is the length of the axes of the dislocations and r_0 and W_i are quantities which we shall discuss. According to ordinary elastic theory, the stresses go to infinity as one approaches the axis of a dislocation. Actually, however, it is necessary to consider the atomic crystal lattice rather than an isotropic, elastic continuum in the region near the axis of a dislocation. If this is done, the stress and strain are found to remain finite at the axis. We have therefore used ordinary elastic theory outside a cylinder of radius r_0, where r_0 is the distance from the axis of the dislocation at which the strain is one-tenth. The first term in Eq. (10) represents the elastic energy contained in the region outside the cylinders. The term in W_i represents the energy contained inside the two cylinders. Atomic concepts have been used to calculate the energy inside the cylinder r_0 in the case of rocksalt.[10] If we assume that this energy is proportional to the elastic part of the energy of an isolated dislocation in a cylinder of radius 10^{-4} cm and that the constant of proportionality is the same for all materials, we can use the foregoing result for rocksalt to calculate the constant of proportionality. A dislocation at the center of a cylinder of radius 10^{-4} cm has about four times as much strain energy outside r_0 as there is inside. In passing, it should be remarked that we have omitted certain small terms from Eq. (10); these terms amount to about one-tenth of the total strain energy W.

Using Eq. (10) we can calculate the total strain energy per unit volume as follows. If the average distance between dislocations is R, then the average volume occupied by a pair whose axes are of length l is $\pi R^2 l$ and the average number of pairs per unit mass of metal is

$$N=1/\pi R^2 ld,$$

where d is the density of the material. Thus, from Eq. (10), the energy per unit mass is

$$E=NW=\frac{1}{\pi R^2\lambda d}\left[\frac{mG\lambda^2}{2\pi(m-1)}\log\frac{R}{2r_0}+2W_i\right]. \qquad (11)$$

This calculation involves the assumption that the axes of all dislocations are parallel, which is undoubtedly the case in each mosaic block.

The density of dislocation pairs is $1/\pi R^2$. Hence, according to Eq. (11), E is approximately proportional to the density of dislocation pairs. Since each dislocation is, on the average, associated with a definite amount of strain, this means that the strain energy increases linearly with the

[10] Huntington, Phys. Rev. **59**, 942A (1941).

strain. The experimental results quoted are in agreement with this prediction except at large values of the strain, where the stored energy of certain metals approaches a saturation value. We do not know why the stored energy approaches a constant value. It may be that when the strain is large, dislocations diffuse out of blocks as rapidly as they are being put in.

Tables II and III give the data used and the results obtained for the saturation energy stored in severely cold-worked metals. We have made the calculations for three different arrangements in a highly worked material: (1) the dislocations present as randomly distributed dislocation pairs; (2) the dislocations arranged in the rectangular lattice shown in Fig. 7; (3) the dislocations arranged in the diagonal lattice shown in Fig. 8. For the second and third arrangements, we have taken $a=b$ (see Figs. 7 and 8). The separation distances required to give agreement with experiment are roughly the same multiple of the lattice constant for all of the materials considered. Furthermore, the separation distances agree qualitatively with those found in the theory of work hardening and in the theory of the approach to magnetic saturation. In the case of aluminum, the separation distance in a highly worked specimen is 0.62×10^{-6}, 0.93×10^{-6} or 0.78×10^{-6} cm, depending on how the dislocations are arranged.

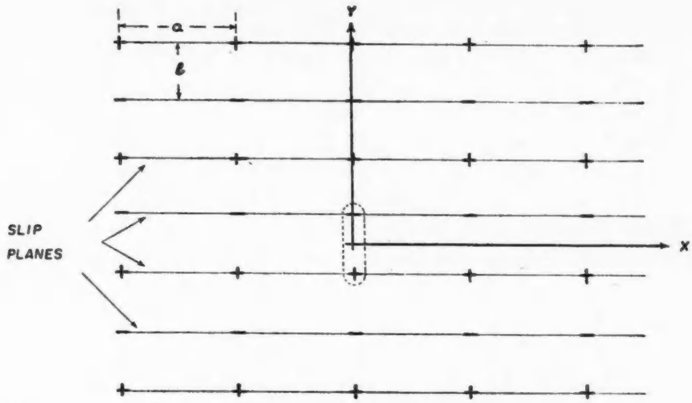

FIG. 7. Rectangular lattice of dislocations.

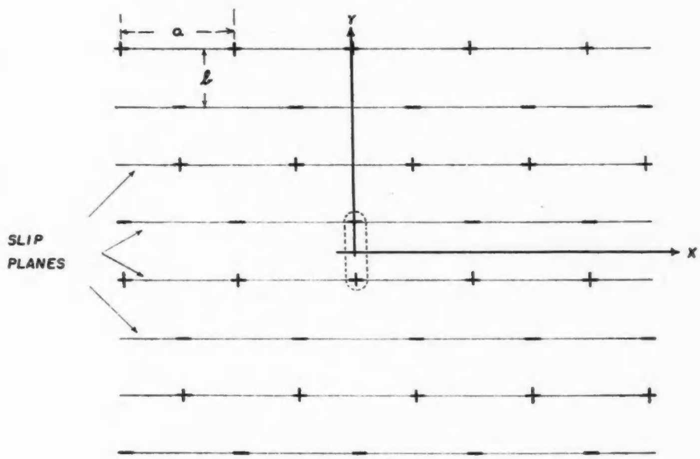

FIG. 8. Diagonal lattice of dislocations.

MAGNETIC PROPERTIES

It is known that the maximum permeability of ferromagnetic materials decreases and their hysteresis in weak magnetic fields increases with cold working. (See Fig. 9.) Not much quantitative data regarding these properties have been obtained.[11] The influence of cold working on the approach to magnetic saturation has been investigated more thoroughly. It is found that the magnetization J near saturation is given by[12]

$$J=J_s-(a/H)-(b/H^2)+cH, \qquad (12)$$

where J_s is the saturation magnetization, H is the magnetic field strength, a is a parameter that

[11] For a discussion and for references to original work see Becker and Doring, *Ferromagnetismus* (Springer, 1939), pp. 147–76; Bitter, *Introduction to ferromagnetism* (McGraw-Hill, 1937), chap. 7. Figure 9 is from Tammann, *Lehrbuch der Metalkunde* (ed. 4, 1932), p. 177.

[12] Kaufmann, Phys. Rev. **57**, 1089A (1940); Becker and Polley, Ann. d. Physik **37**, No. 7, 534 (1940).

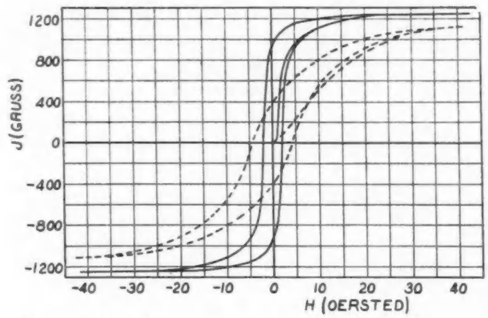

FIG. 9. The influence of cold working on the ferromagnetic properties of iron. The full lines give the magnetization and hysteresis curves for an annealed specimen; the dotted curves were obtained after the material had been plastically deformed. [G. Tammann.]

increases with the amount of cold working, b is a parameter that depends slightly on the amount of cold working and c is a constant independent of plastic deformation. The term a/H is of importance when J is within a few percent of saturation.

If stresses are present in a solid, then it is found experimentally that the material can be most easily magnetized in certain directions. For example, a cylinder of nickel under tension is most easily magnetized in a direction perpendicular to the cylinder axis. If the cylinder is subjected to a compression along its axis, then the specimen is most easily magnetized along the axis. The experimental facts associated with magnetostriction can be explained by assuming that each element of volume possesses a magnetic energy which depends upon the magnitudes and directions (relative to the crystallographic axes) of the external magnetic field, the magnetization and the stresses at the point in question. Thus the presence of internal stresses that vary from point to point will lead to a situation in which the total magnetic energy of the entire crystal will assume its minimum value only if the direction of the magnetization varies from one region to another.

Kersten[13] has shown that many of the changes which take place in ferromagnetic materials during cold working can be understood if one assumes that nonhomogeneous internal stresses are produced in the solid during plastic deformation. Kersten has not given any detailed account of the way in which the internal stresses arise.

[13] See Becker and Doring, reference 11.

Brown[14] has used the dislocation theory in discussing the approach to magnetic saturation. We shall merely outline his calculations and give his results. Suppose that a strong field H is applied to the specimen in the Z direction. The magnetization $\mathbf{J}$ is equal to the saturation magnetization throughout the material, but in some regions it is not quite lined up with the external field. On the average, the components perpendicular to the external field will cancel out. The average component in the field direction is

$$\bar{J}_Z = J_s(1-\tfrac{1}{2}\bar{\alpha}^2-\tfrac{1}{2}\bar{\beta}^2), \tag{13}$$

where J_s is the saturation magnetization, $\bar{\alpha}^2$ is the average over the crystal of the square of the direction cosine between the X axis and $\mathbf{J}$, and $\bar{\beta}^2$ is the average of the square of the direction cosine between the Y axis and $\mathbf{J}$. The problem will be solved if the average values of the direction cosines can be calculated as functions of the external field H and the density of dislocations. Brown assumes that the dislocations are present in pairs, each pair consisting of a positive and a negative dislocation. He claims that the experimental arrangement used by Kaufmann is such that the axes of all the dislocations may be taken parallel to one another and that the external magnetic field is perpendicular to both the axes of the dislocations and the slip direction. It is therefore assumed that the axes of the dislocations are parallel to the Y axis. Since no external stresses act in the Y direction, $\bar{\beta}^2$ is zero. The behavior of α in the vicinity of an isolated dislocation pair is found by requiring that the total magnetic free energy of the specimen be a minimum with respect to variations of α. At points close to the axis of a dislocation, α falls off exponentially with increasing distance. At large distances from a dislocation pair, α decreases as the reciprocal of the square of the distance from the pair. The average of α^2 is then calculated. The average magnetization in the field direction is found to be

$$\bar{J}_Z = J_s\left[1-\frac{NA}{(H^{\frac{1}{2}}+B^{\frac{1}{2}})^4}\{(H+4H^{\frac{1}{2}}B^{\frac{1}{2}}+B)X^2 + (H+4H^{\frac{1}{2}}B^{\frac{1}{2}}+5B)Y^2\}\right], \tag{14}$$

[14] Brown, Phys. Rev. 58, 736 (1940); 60, 139 (1941).

where $N[=1/\pi R^2]$ is the density of dislocation pairs, A is a constant and B is the magnetic induction, $H+4\pi J_s$. The distance of separation R of the two dislocations making up a pair is $(X^2+Y^2)^{\frac{1}{2}}$. In the range in which data are available—$0.1<H/4\pi J_s<1$—Eq. (14) can be approximately written as

$$\bar{J}_Z=J_s-(a'/H)-(b'/H^2). \qquad (15)$$

The best fit with the experimental data is obtained by taking $R\sim(2\times10^{-6}/S)$ cm, where S is the shearing strain. If this is done, the parameter a' is of the same order as the experimental parameter a; over most of the range of shearing strain considered, a' is somewhat less than a. The major portion of the term b/H^2 can be understood without using dislocation theory. Brown finds that the parameter b' is of about the right size to explain the slight dependence of b on the amount of plastic deformation.

DENSITY AND ELASTIC CONSTANTS

The density of a solid decreases with cold working. The change is of the order of 0.1 percent. Table IV lists values for the decrease in various severely cold-worked materials.[15]

Experimentally it is found that the elastic constants of a metal decrease slightly when it is cold-worked. For small amounts of deformation, the elastic constants decrease linearly with the strain.[16] As the strain is increased the elastic constant decreases to a certain minimum value and then, for larger amounts of deformation, rises slowly. The maximum decrease in the elastic constants varies from 1 to 10 percent. The change in Young's modulus for copper is from 6 to 9 percent of the value of this modulus for the annealed material. In the case of aluminum the reduction is 4 percent while for iron it is 3 percent.

The change in density produced by cold work can be understood in the following way.[17] It is known experimentally that the elastic constants of a solid decrease slightly when a dilatation of the solid occurs. Thus, if we have internal stresses present in the solid, the strain energy which varies linearly with the elastic constants can be made a minimum by allowing a slight dilatation of the solid.

Let us examine the situation more carefully. We shall consider a specimen which is not subject to external forces but which has been severely cold-worked. According to Hooke's law, the dilatation θ is

$$\theta=(\sigma_X+\sigma_Y+\sigma_Z)/3K, \qquad (16)$$

where σ_X is the tensile stress across a plane normal to the X axis and K is the volume modulus of the material. Since there are no external forces acting on the specimen, the volume averages of the stresses over the specimen are zero. Thus, if K is constant, the average value of θ is zero and the density is the same for a work-hardened material as it is for an annealed material. However, K is not constant; it changes slightly if the dilatation at the point in question changes. The change in K can be taken into account by using the volume modulus appropriate for small stresses in the Hooke's law term and adding a correction term. The correction term resulting in Eq. (16) is a polynomial of the second degree in the stresses. Furthermore, it must be a scalar quantity because θ is a scalar. It can be shown that these requirements can only be satisfied if we put

$$\theta=(\sigma_X+\sigma_Y+\sigma_Z)/3K_0+AW_d+BW_s, \qquad (17)$$

where K_0 is the volume modulus appropriate for small stresses, A and B are constants, W_d is the strain energy per unit volume produced by dilatation alone and W_s is the strain energy per unit volume produced by shearing strains only. Zener uses experimental data on the variation of elastic constants with pressure to determine the constants A and B. If we average θ over a cold-worked specimen containing internal stresses, we find that

$$\bar{\theta}=+A\bar{W}_d+B\bar{W}_s. \qquad (18)$$

TABLE IV. The maximum percentage decrease in density during cold work.

	Cu	Al	Fe
Calculated:			
dilation only	0.135	0.039	0.153
shear only	0.042	0.080	0.064
Observed	0.3	0.3	0.4

[15] Kawai, Sci. Rep. Tohoku Imp. Univ. **20**, 681 (1931); Schmid and Boas, *Kristallplastizitat* (Springer, 1935), p. 212.
[16] Lawson, Phys. Rev. **60**, 330 (1941).
[17] Zener, Trans. A.I.M.E. **147**, 361 (1941).

Zener then supposes that the internal strains are all dilatations. In this case the second term in Eq. (18) is zero and, by inserting the experimental values for the stored energy given in Table I for $\bar{W}_d$, we can calculate the change in the density of a severely cold-worked solid. The change in the density of a cold-worked material is also calculated under the supposition that all the strains are shearing strains. Table IV contains values for the percentage change in the density of highly worked materials calculated by means of the foregoing theory. In these calculations, use was made of the constants given in Zener's paper. It would be interesting to see whether dislocation theory would give a value for $\bar{W}_d/\bar{W}_s$ that would yield good agreement with the experimental changes in density.

The average dilatation predicted by Zener's theory can be used to calculate the change produced in the elastic constants by cold working. We have seen that experimentally the elastic constants decrease slightly if the volume of a specimen is increased. Thus, the spatial average of an elastic constant over a cold-worked specimen can be obtained by using the value for the average dilatation together with the experimental data on the change of the elastic constant with volume. The calculated reductions in the elastic constants of a highly cold-worked metal are somewhat too small. For example, the calculated change in the volume modulus of copper is 1.3 percent or less, whereas the observed change is from 6 to 9 percent. In iron the calculated change is 1.1 percent or less, whereas the observed change is 3 percent. Further measurements of the changes in the elastic constants of single crystals produced by cold working might resolve the discrepancy.

ELECTRIC RESISTANCE

The electric resistance of a metal increases when the metal is cold-worked. The increase for severely worked materials is usually several percent of the specific resistance of the annealed metal at room temperature.[18] In the case of tungsten, the increase is quite large, amounting to 34 percent of the specific resistance of the annealed material at room temperature.[19] The dependence of the increase of resistance on the strain is not yet known. In Table V are listed values for the maximum increase of resistance observed in various polycrystalline materials at room temperature.

TABLE V. Values of the maximum increase in electric resistance during cold working, expressed as percentages of the resistance of the annealed metal measured at 20°C.

Cu	Ni	Mo	Ag	W	Pt
2–3.5	8	18	3	30–50	6

According to the electron theory of metals, the electric resistance of a metal is produced by the deviations of the crystal from perfect periodicity. For example, the thermal oscillations of the atoms constitute a deviation from perfect periodicity and produce a large part of the electric resistance of most pure metals. The distortions of the crystal lattice near the axis of a dislocation also constitute a deviation from perfect periodicity, and we should expect that the electric resistance of a specimen would increase as the density of dislocations in the specimen increases.

The theoretical evaluation of the electric resistance produced by large numbers of dislocations is rather long and involved. Because of this we shall merely state the results of the calculation. First, the electrons near the top of the filled energy levels in the conduction band have wavelengths of about 1A. The dislocations in a highly worked metal are separated by distances that are equal to or greater than 10^{-6} cm. Because of the difference in these two distances we find that there are no interference effects produced by the lattice-like array of dislocations. Thus the scattering produced by n dislocations will simply be n times the scattering produced by a single dislocation. Second, calculation shows that the scattering produced by a single dislocation is essentially small angle scattering. If d is the angle between the initial direction of the electron and its direction after it has been scattered by the dislocation, then the probability of scattering

[18] Schmid and Boas, *Kristallplastizitat* (Springer, 1935), p. 24; Smart, Smith and Philips, Trans. A.I.M.E. **143**, 272 (1941); Crampton, Burghoff and Stacey, Trans. A.I.M.E. **143**, 229 (1941).

[19] Geiss and v. Liempt, Zeits. f. Physik **41**, 867 (1927).

turns out to be proportional to $1/d^2$. Third, the calculated change in the electric resistance of a severely cold-worked metal is smaller than the experimental value by a factor of ten or more. This clearly indicates that the change in the resistance is not due to the presence of dislocations in cold-worked material. The effect may be due to a decrease in the size of the small single crystals making up the specimen or to some change in the mosaic structure. It would be of interest to see whether the increase in the electric resistance of single crystals during cold working is as large as the change observed for polycrystalline materials.

CONCLUSION

In conclusion, it might be well to point out that we have limited our discussion to experimental effects which arise from changes in the density of imperfections in the material investigated. We have not discussed such topics as the creep of metals, the dependence of internal friction on plastic deformation, or recrystallization because these subjects would seem to involve a treatment of the formation, the motion and destruction of imperfections. Although some work has been done in this connection,[2] in our opinion only very little is known theoretically about the dynamics of plastic deformation.

Galileo Galilei, 1564–1642, and the Motion of Falling Bodies

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IN August, 1638, a young Englishman of twenty-nine visited a blind old man of seventy-four at a villa in Arcetri a mile from Florence. Six years later in one of the imperishable classics of English prose he referred to the visit in the following terms:

> And lest some should persuade ye, Lords and Commons, that these arguments of learned men's discouragement at this your Order are mere flourishes and not real, I could recount what I have seen and heard in other countries, where this kind of inquisition tyrannises; when I have sat amongst their learned men, and been counted happy to be born in such a place of philosophic freedom, as they supposed England was, while themselves did nothing but bemoan the servile condition into which learning amongst them was brought; that this was it which had damped the glory of Italian wits, that nothing had been there written now these many years but flattery and fustian. There it was that I found and visited the famous Galileo grown old, a prisoner to the Inquisition for thinking in astronomy otherwise than the Franciscan and Dominican licensers thought.

The old philosopher's course was nearly run when he received John Milton as a guest—a meeting that has stimulated the imagination of several artists. One would give a good deal to know what they talked about, the one a scholar and a poet, the other a scholar likewise and a scientist; the one at the beginning of a career which was to bring glory to English letters, the other an old man suffering from many ills, denied the glory that he had rightfully earned but still persisting to the end in the study of the book of nature, which he always insisted was the only true book of philosophy. In the very year of the visit just mentioned there was published in Leiden Galileo's last great work: *Discourses and Mathematical Demonstrations concerning Two New Sciences pertaining to Mechanics and Local Motions*. Because of the difficulties with the Inquisition the book could not be brought out in Italy, and when it finally appeared the author had reached the stage where he could only fondle the volume and turn the pages; loss of sight prevented him from following the printed words that we have long recognized as the foundation of classical mechanics.

The progress of science, like other phases of human evolution, is full of ironies. Galileo's persecution by the Holy Office resulted primarily from his astronomical discoveries and his championing of the Copernican theory. Though these contributions were noteworthy and have long excited the popular imagination, they do not constitute his greatest contribution to modern civilization. It is now agreed that the latter was his theory of mechanics, which laid the ground-

work for his distinguished successors, Huygens and Newton. This is an interesting illustration of the curious shift in emphasis between Galileo's time and our own. In all the turmoil of praise and detraction, defense and persecution that gathered round his declining years it is unlikely that many of his contemporaries realized clearly his position as the founder of the method of theorizing which was to make physics the most successful of all the sciences in the description of nature.

The details of Galileo's life have been so often reproduced that in this, the three-hundredth anniversary year of his death, it is unnecessary to recite them. When once the fictional biographers have got hold of a hero's private life it is useless for others to rehash it. Doubtless many have read *The Star Gazer*, by Harsanyi; certainly it is a successful book of its kind, though it fails to put appropriate emphasis on Galileo as a physicist. The author probably felt that very few people care anything about physics anyway, even if they know what it is. It is another of life's little ironies that it takes a highly technical war like the one in which we are engaged to introduce the man on the street to the place of physics in contemporary civilization—an expensive and tragic method of instruction.

For our present purpose it will suffice to recall that, living as he did from 1564 to 1642, Galileo spanned with his labors parts of two centuries—a period marked by a genuine evolution from medieval to modern thinking in science. Note the emphasis on the word *evolution*. Popular writers have made it fashionable to talk about the twentieth century *revolution* in physics, and it is all too easy for the layman to get the impression that physics progresses by violent overturnings of accepted ideas. This is of course far from true, as is well illustrated by the work of Galileo. Somewhere Maxwell has spoken of the theory of the magnetic field due to electric currents as "leaping full-grown and full-armed from the brain of Ampère, the Newton of electricity." Many people have accepted the view that in similar fashion the laws of motion leaped in their final form out of the head of Galileo. This view is erroneous, and therein lies much of the interest the great Tuscan holds for the modern student. It must not be forgotten that Galileo was a child of his century. All scientists are; the emphasis often laid on the timelessness of scientific thinking is not borne out by a careful study of its historical development. Science, like all other kinds of human activity, is a function of the spatial and temporal environment. It is true that, because of the scientist's preoccupation with concrete experience and actual apparatus, the barriers of space and time seem less imposing than in the realm of the arts and letters. We must not forget, however, that science is more than going through operations with gadgets—it involves description of experience, and this has proved to be impossible without the introduction of abstract concepts. The construction of concepts is an activity that apparently cannot be carried out in complete independence of one's environment.

A thoroughgoing assessment of the place of Galileo in sixteenth- and seventeenth-century thought is a considerable task, and we shall content ourselves here with a more modest assignment, namely, a brief estimate of his part in the development of classical mechanics and, in particular, the laws of motion of freely falling and projected bodies. This task in itself allows ample scope for an interesting investigation of Galileo's relations with his predecessors, his contemporaries and his successors. The field has indeed already been explored and it may appear presumptuous for a neophyte to dare to enter where authorities like Fahie, Wohlwill, Duhem, Mach and Koyré have delved so deeply and to such good purpose. But it is at once an attraction and a weakness of the history of science that much of it will forever remain judicious interpretation, which is merely a flossy name for guessing, and surely one is entitled to his guess, even if he succeeds only in being laughed at for his pains. This aspect of the history of science as a professional activity appears not to have been emphasized. When we consider how difficult it is for supposedly intelligent, educated people now alive to understand one another on almost any conceivable topic which in the least transcends the simplest elements of daily life, is it at all surprising that we find trouble in understanding what our predecessors really thought about natural phenomena from their writings or the commentaries of their contemporaries? Is it

Milton visiting Galileo, from the painting by Annibale Galti (*ca.* 1877).

not inevitable that modern preconceptions and prejudices will be read into ancient texts? And does this not imply that the history of science takes its place with other branches of science as a discipline in which the theory of what things mean is as important as the facts themselves? It will be helpful to keep this in mind as we venture on our discussion of the development of Galileo's ideas on motion.

To the modern physicist and, indeed, to the modern cultivated nonphysicist who has been properly conditioned by a college course in elementary general physics, motion seems to be such an obvious thing that it is surprising there could have been so much disagreement over its nature in classical antiquity and the Middle Ages. When freshmen fail to comprehend the laws of falling bodies and projectiles we tend to attribute it to inherent stupidity or inattention to duty.

How could Aristotle possibly have gone so wrong in his theory of motion? To us the facts appear so simple that we can read the elaborate verbalisms of the *Physica* only with the greatest impatience—until we stop to reflect that Aristotle was not interested in the kind of questions we are accustomed to ask about motion. To us, and this is, of course, an inheritance from the later work of Galileo, the theory of motion means the precise description in mathematical terms of actually observed motions. But this was not at all what Aristotle meant by a theory of motion. Starting out with the postulate that the natural state of order in the universe is *rest*, he was forced by his philosophy to seek a *cause* for motion as a transient disturbance. He went about this by dividing all motions into two classes, *natural* and *violent*. Every object has a natural place in which it will remain at rest unless disturbed. Natural motion is the result of an attempt on the part of a body to regain the natural place from which it has been displaced; the freely falling body is striving to get to its natural resting place, which is as near to the center of the earth as possible. On the other hand, every violent motion is a disturbance of

order: its explanation gave Aristotle more trouble. He was committed to the idea that the cause of violent motion may be found only in direct material contact with the moving body; action at a distance he shunned as we do in present-day field physics; but, alas, Aristotle had no "field" to fall back on—that had to wait for Faraday. So to him, violent motion demanded the continuous action of an external mover joined to the moving body; when the external mover ceases to move or becomes separated from the body the latter also ceases forthwith to move. The motion of a projected body thus provided Aristotle considerable difficulty: here is a case of continuous motion with no apparent mover. He was thus forced to explain it by some reaction of the surrounding medium. His "explanation" failed to satisfy all his scientific successors of the Middle Ages; even his faithful adherents could not wholly swallow it, and the independent thinkers made it the spearhead of their attack on Aristotelian physics in general.

Another peculiar feature of Aristotle's physics which caused his scientific descendants no end of trouble was his denial of the possibility of the existence of a vacuum. This was tied in with his theory of motion in an ingenious way. Since in Aristotle's view the velocity of a freely falling body is proportional to the *quotient* of the weight of the body and the resistance of the medium, it necessarily follows that in a vacuum where there is no resistance, all bodies will fall with infinite velocity. But this has never been observed. Moreover, in a vacuum violent motion could never take place, since there would then be no medium available to serve as mover. It is small wonder that Aristotle could not bring himself to believe in the vacuum as a real thing. Of course, he might accept it as a mathematical fiction—the abstract construct for Euclidean space—but into mathematical space one must be careful, according to Aristotle, to place only mathematical figures; there is no room therein for real physical objects: he was very reluctant to mingle physical reality with mathematical abstractions. His empiricism in this respect prevented him from founding theoretical physics.

It is a curious fact that Archimedes, the greatest physicist of antiquity, left no works on motion. From the way in which he treated the problems of static equilibrium one might hazard the guess that if he *had* made a study of motion he would have anticipated Galileo. Perhaps he felt the whole thing was too obvious, of no practical importance and not worth the serious mental effort of a philosopher.

When we come to the medieval philosophers whose views on motion might have been expected to exert some influence on Galileo's thinking, our attention naturally turns to the lecturer in natural philosophy under whom he sat in his student days at the University of Pisa. This was Francisco Bonamico, the Florentine, whose lectures were published in 1611 in a large volume entitled *De Motu.* Galileo was evidently an independent pupil, and if he received any stimulus from his teacher it was to disagree with Aristotle and look further for the explanation of motion. Bonamico represented medieval Aristotelianism in an elaborate, albeit rather confusing way. At any rate it is extremely difficult for us to put ourselves in the place of Bonamico and think of motion as he thought of it. He undoubtedly felt keenly the difficulties of Aristotle's theory of falling bodies. The outstanding one of these was the puzzle: why should a *constant* cause—the weight of a body—produce a variable effect—the accelerated motion? It is not on record that Aristotle himself was much worried over this question: since all freely falling bodies tend to reach their natural place, it is also natural that they should strive in increased fashion as they approach the goal. The medieval commentators evidently felt this was too easy a way out. They wanted to connect the tendency to seek the natural place with some independently observed characteristic of the body and seized on the weight as most reasonable for the purpose. Hence their dilemma. Inevitably an Aristotelian like Bonamico was led to the solution by the assumption that the resistance of the medium decreases during the fall or, at any rate, that its interaction with the motion somehow adds continually to the assumed constant effect of the weight.

On the other hand, the medieval period did not lack violent critics of Aristotle. The names of Buridan and Oresme of the Parisian school of the latter part of the fourteenth century and, of

course, Leonardo da Vinci immediately come to mind. Typical of the anti-Aristotelian viewpoint and more important for our present purpose because closer to the Galilean period was Jean Baptiste Benedetti (1530–1590). It seems certain that Galileo was familiar with his *Diversarum speculationum mathematicarum et physicarum Liber* of 1585, though curiously enough there appears to be no explicit reference to him anywhere in Galileo's writings. In his treatise Benedetti summarized his adherence to the school of the "impetus" theory, already suggested by the Parisians. This discards Aristotle's theory of the effect of the medium on the motion of a body by insisting that every object, whether set in motion naturally or violently, receives an "impetus" (this was actually the Latin word used, though it was often replaced with the term *impressio motus*), so that even when separated from the origin of its motion—for example, the hand—it can continue to move by itself. In natural motion the impetus increases without limit, whereas in violent motion its effect is to make the body thrown into the air lighter than normal. Moreover, by hurling with a sling more impetus can be stored and the resulting motion protracted. It is clear that Benedetti was still following in Aristotle's footsteps in seeking a *cause* for violent motion, but he was searching for it in a quite different fashion and manifested considerable impatience with the "errors" of the master. How medieval and yet in another sense how modern are the words with which he expresses his attitude toward the great philosopher of antiquity:

> Such is the greatness and authority of Aristotle that it is difficult and dangerous to write against his teachings, and to me in particular since I have always held his wisdom a matter for admiration. Nevertheless, impelled by zeal for truth, by the love of which he himself, if he were living now, would be actuated, I have not hesitated in the interests of all to state wherein the unshakable foundations of mathematical philosophy force me to dissociate myself from him.

One cannot examine writings such as those of Bonamico and Benedetti without being vividly impressed by the fact that the problems of motion which they were discussing are quite different from the problems in which we are interested today. Thus Benedetti, like Aristotle, is really intrigued by what we call the *initial* conditions of the motion, that is, how it happens that when motion is communicated to a body by the hand, the body continues its motion after the removal of the hand. The modern physicist has no interest in this matter: it has been completely sidestepped, as it were, by the introduction of the concept of *inertia*. This is an interesting illustration of one way to solve problems. It is still the fashion in popular books and elementary treatises to expatiate on the errors of our forebears in scientific matters. We forget that they were often trying to solve problems which no longer have any appeal. It must be remembered that what we call physical explanation varies from age to age: there never will be an *absolute* criterion of its meaning.

It has already been emphasized that Galileo's ideas on motion underwent a gradual development. This is very clear from an examination of his early work composed in Pisa and published under the title *De Motu* in 1590. Here the young philosopher showed himself a violent and not always discriminating anti-Aristotelian. In the rather cocky enthusiasm of youth he was quite certain that Aristotle was all wrong. But, like Benedetti, he was really still fettered by the old Aristotelian tradition. He was still trying to answer the same old question: *why* do bodies move as they are observed to do? It was clear to him that the answer must be found in the impetus theory, the concept of *impressed force*. He was not satisfied that this idea had been handled properly by his predecessors and contemporaries, so he gave it a thoroughgoing overhauling. The result was an ingenious development, but it makes strange reading for those accustomed to hear Galileo acclaimed as the founder of classical mechanics and modern physics.

The *impressed force* idea probably was clearer with Galileo than with any of his contemporaries. He visualized it as a quality which, like heat or cold, can be transferred from one body to another. When transferred it becomes the property of the body to which it goes and no longer has anything to do with that from which it has come. This avoids Aristotle's difficulty about the necessity of the presence of a continual mover attached to the moving body. But the

impressed force always dies away eventually—no motion endures forever. It is clear that the idea of inertia was far from Galileo's mind at this stage.

It is interesting and rather surprising to learn that in *De Motu* Galileo strenuously insists that the velocity of a freely falling body is proportional to its weight. Of course, he recognized the initial acceleration of the falling body but was sure that ultimately the velocity would attain a constant value which could actually be observed if only the body could be dropped from a sufficiently high tower. This is strange language from the man who is popularly supposed to have revolutionized science by dropping balls of different weight from the famous leaning tower to destroy at one fell swoop the whole Aristotelian fallacy. As a matter of fact, it is not certain that this experiment was ever performed. However this may be, it *is* a curious coincidence that in his assumption of a constant final velocity for a falling body, Galileo was not so far off: we know that this is actually brought about by the *resistance* of air. The incautious observer might then conclude that this is another of those much talked about early anticipations of modern truth. The history of science is full of such pitfalls. A careful reading provides no justification for the conclusion. Galileo undoubtedly felt that Aristotle had made such a botch of the influence of the medium that an entirely new conception was necessary. His own idea is quite clear from the example he gives of the reason a ball rises when thrown up into the air by the hand: it is because the hand impresses sufficient "lightness" in it to overbalance the "heaviness" due to its weight; as long as the *lightness* exceeds the *heaviness*, the ball continues to rise. When the two become equal the ball reaches its highest point, stops and then starts to fall. However, the *lightness* has not entirely disappeared, and as long as any remains it keeps the ball from attaining the final maximum velocity characteristic of its weight. The latter is attained only when all the lightness has disappeared. It is an interesting point of view, actually not completely original with Galileo, since it is suspected that Hipparchus had it in antiquity. But Galileo went further—even the body dropped freely from rest

Galileo and his scholars in Arcetri, from the painting by Niccolò Barabino (1880).

from a high tower has "lightness" impressed in it which provides the check that makes it begin slowly and pick up speed only as it falls. Presumably the "lightness" results from the process of taking it up into the tower in the first place. Some might be tempted to see in this the germ of the idea of potential energy, but let us resist temptation! Galileo claims to have observed experimentally that at the beginning of fall, light bodies fall faster than heavy bodies. This can be "explained" by assuming that it is harder to impress lightness in a light body than in a heavy body. Hence at the beginning of free motion light bodies have less lightness in them to oppose the downward motion.

We have implied that Galileo would have nothing to do with the medium as a *vehicle* for motion. This is true, but it must not be understood to imply that he neglected the medium entirely. It is clear that he, like Benedetti, was greatly influenced by the work of Archimedes and that the concept of buoyancy, the central notion in Archimedes' famous principle, was the kernel of Galileo's theory of the impetus. This is indeed the basis of his distinction between absolute weight and relative weight and led him to the conclusion that it is only in a vacuum that bodies fall with the velocity appropriate to their absolute weights. Galileo's numerous references to Archimedes are always laudatory; evidently he felt that the ancient physicist was on the right track. It is significant that Galileo's first published work of scientific consequence, his little treatise on the hydrostatic balance (1586), was clearly in the Archimedean tradition.

In the hands of Galileo the impetus theory probably received its most elaborate development. If he had gone no further he would have been recognized as a valiant critic of Aristotle and a medieval philosopher of eminence, but we should not be paying particular attention to him today. It was because he realized the essential failure of the impetus point of view and completely changed his attack on the problem of motion that we remember him. He had tried to develop a better physics than that of Aristotle, yet a physics still based on "common sense"; he had failed. The next step was to look upon the problem in an entirely different fashion; the result was the discovery of the law of falling bodies, announced in Padua in 1604 in the famous letter to Sarpi in Venice. By this time Galileo had decided that it is more profitable to study precisely *how* bodies fall than to speculate *why* motion takes place at all. Why not take motion as something given and examine it with care rather than spend vain hours in trying to understand why human experience should include this sort of phenomenon? In a certain sense it was an expression of defeat: it was a decision to abstract from the totality of experience something that seemed tractable to and manageable by the human mind. It was a momentous decision, for it implied a thoroughgoing break with the Aristotelian tradition and a determination to place the future development of physics on the Archimedean basis. It has colored the whole subsequent history of the science.

Galileo's new method appears clearly in the letter to Sarpi where he says:

> In reflecting on the problems of motion, for which I felt I lacked an absolutely sound and self-evident principle which could be used as an axiom in order to demonstrate logically the properties observed by me, I have finally arrived at a proposition which appears sufficiently natural and evident. Assuming this, I have been able to derive everything else, and in particular that the space traversed in natural motion varies directly as the square of the time. . . . And the principle is this: that natural motion takes place in such a fashion that the velocity varies directly with the distance traversed. . . .

Now the important thing about this statement is not the precise character of the fundamental principle or axiom. As a matter of fact, it does *not* lead to the law of motion stated and therefore represents an error in mathematics on the part of Galileo—a pardonable error perhaps, since he did not have the differential calculus at his disposal. The important thing is that Galileo had decided to abandon the purely empirical method of physical description in which each physical phenomenon is examined in turn and explained as closely as possible in terms of common sense. He now proposed to make physics a deductive science based on concepts which are abstract and principles which are purely postulational and not susceptible to proof, hoping that on this foundation all observed phenomena might ultimately be logically de-

duced. This is what we call today the method of theoretical physics.

Much has been written and more might be written on the reason why Galileo should have tried to base the theory of free motion on the hypothesis that the velocity of fall varies as the distance traversed. The simplest view would be to regard it as another remnant of the Aristotelian tradition which even the medieval critics of Aristotle were unable to discard. After all, the statement that the farther from the origin of fall, the faster the fall, is one of the simplest of observations; and what is more natural than to replace the qualitative connection with algebraic proportionality? To assume that the velocity varies with the square root of the distance would have seemed a violation of the fundamental canon of simplicity.

There is another point of view which may be worth more emphasis than it has yet received: the idea of time as a precise measure of duration was evidently not so clearly grasped by the medieval scientist as the idea of space. Geometry and geometric instruments of precision were familiar to all, but such clocks as existed were sorry affairs. One may say with truth that the metricizing of time was urgently needed in order to develop the science of mechanics. This was accomplished by Galileo, who by 1610 had discovered that the proper way to deduce the law of falling bodies is to assume that the velocity varies directly as the *time*. This involved the introduction of the concept of continuously varying instantaneous velocity which gave his contemporaries no end of trouble, since it implied the idea of motion with infinite slowness, which was hard to swallow. It was easy enough to believe that a falling body passes through every single point of its continuous path to the ground, but to believe that the time of fall is also infinitely divisible was another matter. To the seventeenth-century scientist this was as troublesome an idea as the concept of quantum mechanical differential operators has been for many twentieth-century physicists. Galileo must have been troubled by it himself, for he goes to some pains in his *Two New Sciences* to make it seem plausible by inventing ingenious but imaginary experiments. This is hardly the place for a discussion of this well-worn field. We may merely point out that in the introduction of mental experiments Galileo was invoking a method which has characterized physics ever since his time. Of course, he did actual experiments with inclined planes and the like, and much praise has been showered on him by somewhat undiscriminating admirers who have liked to emphasize his zeal for experimental test of all his conclusions. The melancholy fact seems to be that Galileo's experiments, when it came to precision, were about as bad as most of the elementary physics lecture table demonstrations of our own time. In fact, they were not intended to be precise: they were intended to be suggestive demonstrations, and we should not feel badly that Mersenne complained he was unable to repeat Galileo's experiments and get his results. No, Galileo was not a great experimental physicist—he was the founder of theoretical physics, and that is fame enough for any man.

Rollin L. Charles, 1885–1941

Professor Rollin L. Charles, who had been Professor of Physics and Electricity at Franklin and Marshall College since 1922, died December 13, at his home in Lancaster, after an illness of several months.

Professor Charles was born in Bethlehem, Pennsylvania, November 26, 1885. He was graduated from the Stroudsburg State Teachers College in 1902, and received the B.A. degree from Lehigh University in 1907 and the M.A. degree from the same university in 1910. Subsequently he studied at Lehigh, Columbia University and the University of Pennsylvania. From 1905 he rose from assistant professor to associate professor at Lehigh; and from 1928 to 1930, in addition to his duties at Franklin and Marshall College, he served as Professor of Physics at Albright College.

Since its organization in 1912, he was the managing partner of the firm of Franklin and Charles, publishers of technical books, and with the late Professor W. S. Franklin was co-author of a textbook in the calculus. He was a charter member of the Mathematical Association of America and a member of Phi Beta Kappa, the American Association of Physics Teachers, the American Association for the Advancement of Science and Sigma Pi Sigma. He was also active in various civic organizations.—H. M. F.

Sir Isaac Newton, 1642–1727—A Study of a Universal Mind

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I

Nature and Nature's Laws lay hid in night;
God said, Let Newton be!—And all was light.

It is not every man who has an Alexander Pope to enshrine his name in an epigrammatic couplet; but Newton's fame would still shine gloriously if Pope had never lived.

If a man's greatness may be judged by the opinion of his contemporaries, Newton was certainly among the giants of this earth. It is pleasant to know that his fellows recognized his superiority. Addison praised him; Montague patronized him; he was a friend of Charlotte, Princess of Wales. In his lifetime he was, as De Morgan[1] points out, invested with all the honors once paid to the figure of Aristotle.

Voltaire, another mind of universal stature, said of Newton: "If all the geniuses of the universe were assembled, he should lead the band."[2] Although this unfortunate translation calls up the picture of Newton strutting down the ages in boots and busby, with light flashing from a twirling baton of U (235), there is much truth in Voltaire's statement. Yet Germans would consign the leadership to Goethe; the Italians would press the claims of Leonardo or Galileo; Americans would advance Franklin; and the French might bicker over the contrasted merits of Descartes, Pascal and Lavoisier.

The English, however, were not content to see Newton at the apex of a pyramid, but did their best to turn him into a scientific Stylites, as moral as Moses and as wise as Paul—beyond the reach and almost beyond the comprehension of ordinary men. It is only within very recent years that fuller facts about his life have led to a humanization of this lath and plaster saint, and now that the Portsmouth Collection has been dispersed, the manuscripts which Newton left to his heirs may become public and shed greater light on his career and character.

Newton's character helped to foster the "touch-me-not" attitude that quickly gathered about him. He was extremely aloof: Charles Montague was perhaps the only real friend he ever had; all others—Boyle, More, Wren, Locke and Halley—were but acquaintances.

But however aloof he was in his personal life, he was catholic in his scientific acquaintances. One must not think of him as one thinks of Roger Bacon—a cloistered spirit working out by himself the problems of the cosmos. Newton was a synthesizer first, and from that point went on to deduce his own discoveries from the general body of fact as searched out by any and all. "He was partly to make, and wholly to consolidate, the greatest revolution in human thought about external nature of which we have any record."[3]

He took the work of Copernicus, Brahe, Kepler, Galileo, Bacon, Boyle, Hooke and many others, and welded it into modern science as we now recognize it. And he did it not by classifying the facts on paper, as Bacon had hoped to do, but by integrating them in his mind and using them as tools with which to unlock doors that had heretofore been closed to man. The Newtonian synthesis, as it has been labeled, is one of the most astonishing intellectual feats of any age.

It should be noted that Newton's genius for original work has been emphasized at the expense of his wide scholarship and knowledge of other men's achievements. This has led to the partial eclipse of the reputations of those upon whose work he built. On the other hand, as More[4] points out, ". . . the fame of many of the greatest men of science rests wholly on their verification of special problems in his synthesis." Small wonder he became a demigod!

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[1] De Morgan, *Essays on the life and work of Newton* (Open Court, 1914), p. 48.

[2] Miller, "Newton and optics," in *Sir Isaac Newton, 1727–1927* (Williams & Wilkins, 1928), p. 15. The series of papers comprising this volume was prepared under the auspices of the History of Science Society.

[3] Broad, *Sir Isaac Newton* (Oxford Univ. Press, 1927), p. 3.

[4] More, *Isaac Newton* (Scribners, 1934), p. 241.

Although Newton reconciled the contradictions of the scientific thought of his age, and brought order out of conflicting views, his own life bears many of the marks which we know to have been characteristic of the time. "He experienced what we apologetically speak of as 'straightened circumstances' . . . ," yet he died worth £34,000.[5] "He loved the solitude of a student and yet abandoned it for a life in the social atmosphere of the metropolis. He challenged a royal decree and later accepted a knighthood. He dreaded controversy . . . ," but his years were full of it.[6] "Because he could not subscribe to church dogmas, he declined to take holy orders, and yet he wrote upon and reverenced religion."[6] These are but a few of the more striking contradictions in Newton's life.

He was born at Woolsthorpe, Lincolnshire, in 1642, the year of Galileo's death, and was brought up by a widowed mother who soon remarried. At the customary age, he was sent to Grantham where he attended the King's School, a foundation that had trained Henry More and later was to count Colley Cibber among its students. The most striking feature of his school days was his mechanical skill; all his life this dexterity stood him in good stead, and the youthful experience of making sundials and water clocks was to help later when he came to work with prisms and telescopes.

In 1661, Newton went up to Cambridge, where he enrolled at Trinity, his uncle's college. Here he had rooms on the same staircase which later housed Macaulay and Thackeray. The influence of Isaac Barrow, the great divine and mathematician, was a powerful factor in Newton's college life.

It was a stimulating environment. Newton began to experiment in earnest, and his account books of the period (1665) give us a cryptic, but none the less human, insight into the life he led. The sums he spent went for widely different objects: a Stilton cheese, at 2s.; a tavern bill, 2s.6d.; a magnet, 16s.; a chamber-pot, 2s.6d.; compasses, 3s.6d.; oranges for his sister, 4s.2d.[7]

The years 1664–1665 were Newton's golden age. If we except the period in which Shakespeare wrote *Hamlet*, *Othello*, *Lear* and *Macbeth*, it is probably true that no human brain ever accomplished as much in a few years as did Newton at this particular time. Cambridge was closed for some of the period because of the plague, and in his country retreat Newton worked out the elements of the binomial theorem, discovered and developed fluxions, ground lenses in shapes other than spherical, experimented with color and did his first work on gravitation. The three last achievements were accomplished in a space of three months!

On May 20, 1665, Newton wrote down his first thoughts on fluxions—one of the two branches from which integral and differential calculus have grown. Newton continued with five papers developing his system, which was founded on the work of Wallis, Descartes, Barrow and Fermat. When he had done, he must have known the value of the work, for he always estimated his accomplishments at their true value, but he made no effort to impart it, keeping it as a tool for his own use. More ascribes this in part to his attitude toward pure mathematics:

> . . . as an end in itself, he considered mathematics to be a dry and barren subject; he valued it only as a tool and a language for the expression of natural law. Thus, while he made inventions of first-rate importance, he made them for his own use; he rarely developed them systematically and had no desire to publish them for the use of others.[8]

This attitude led to several unhappy quarrels later in his life, and shows that Newton did not have a clear conception of the true brotherhood which we like to believe exists among all scholars. There is no evidence that he regarded the handmaiden, Truth, as his own concubine, to be kept jealously guarded from the sight of other men; he was simply too much interested in his own problems to think that his discoveries would be of help to others. A human catalyst was always necessary to prod him into further discoveries and to force him to share the results of his studies. Such men, fortunately, were not lacking.

Here at Woolsthorpe Newton did his first work on gravity. The legendary apple seems to

[5] Smith, "Newton in the light of modern criticism," reference 2, p. 8.
[6] Smith, reference 5, p. 9.
[7] More, reference 4, pp. 53, 54.

[8] More, reference 4, pp. 56, 57.

have been real enough, but it did not hit his head—he watched it fall as he stood at a distance. Why did it fall? With what acceleration did it drop? Newton was not the first to whom these questions had occurred, nor the first to try to find the answers. Galileo had studied the problem and had made some progress. The distance of the object from the earth was known to be a factor; what was the law? Was the law, if one could be established, applicable to bodies beyond the influence of the earth? It was known that the moons of Jupiter were subject to Kepler's laws; the force acting there was, therefore, probably the same as that in the case of the planets and the sun—the force which we call gravitation.

Newton worked on the mathematical relationships of the problem at this time, and he and Huygens independently found the formula for centrifugal acceleration. Newton went further and worked out the lunar aspect of the puzzle.

Having arrived at this position, why did not Newton announce his work? This is one of the questions that has been debated since the early eighteenth century. Aside from the personal characteristics which entered into his reluctance to publish, it seems probable that the delay resulted because Newton had other interests, and put the work aside since he was not satisfied with the accuracy of the figures. There were also some theoretical difficulties in the lunar problem. The work was done; it lay hidden for 20 years.

In 1663, James Gregory, a Scottish scientist, had proposed that a telescope be constructed on principles of reflection, rather than refraction. Newton had been bothered by chromatic aberration in the existing telescopes and adopted Gregory's suggestion, with minor changes. In 1668 Newton constructed a small reflecting telescope and made some observations with it; shortly afterwards he made a slightly larger tube which he sent to the Royal Society. These were the first instruments of their kind. Newton's gift may still be seen in the Society's museum.

The gift of the new telescope attracted widespread attention, both in Cambridge and in London. It may have had some bearing on the fact that when Isaac Barrow resigned the Lucasian Professorship of Mathematics in 1669, Newton—who had been elected a Fellow of Trinity two years before—was appointed to the place. A full professorship at Cambridge at the age of 27 was a record of sorts, even in the seventeenth century!

Newton's work with the telescope and his pondering of color distortion—chromatic aberration—led him to the study of colors. He wrote his first published scientific paper on this subject; it appeared in the Royal Society's *Philosophical Transactions* in 1672. The style of the paper was noteworthy; it was clear, simple and direct, with none of the frills and furbelows which usually encumbered such writing in that period. Of the piece, More says:

> . . . it is almost perfect in both form and content. It is the more remarkable because Newton had no example to follow; it is significant of his genius that his first essay was as perfect as was his later work. His mind seemed to need no period of growth but to have reached its full maturity at once.[9]

The content of the paper was the chief thing, however. Newton had been experimenting with prisms—he had bought his first in 1666—and had shown that white light was of composite nature. He had discovered the spectrum; from this paper stems the whole science of spectroscopy and much of modern optics. Broad thinks that this was Newton's greatest contribution to optical science.

The paper established his scientific reputation, if there had been any doubt of it before; his position had been consolidated by his election on January 11, 1671/2 to the Royal Society. In this year Newton also published his edition of Varenius' *Geographia generalis*, which had first appeared in 1650. This he accomplished in connection with his teaching duties. Teaching, writing and experimenting did not complete the roll of Newton's activities, however. He was at the same time developing his system of fluxions, and was also very busily engaged in chemical research.

Not many people think of Newton as a chemist, and still fewer think of him as an alchemist. At that period chemistry was just emerging as a true science, under the guiding hand of Boyle; Newton was a little early, or he might have done more important work in the

[9] More, reference 4, p. 77.

field. The faint opprobrium which has become attached to the word "alchemy" is unfortunate; not all alchemists were quacks and deceivers. Newton certainly was not. He worked, wholeheartedly, to find the Philosopher's Stone, and even may have had visions of discovering the Elixir of Life. Somehow these hopes do not seem so absurd to us as they did a decade ago; the wheel has come full circle perhaps—Newton's chemical goals are again in fashion.

In the Portsmouth Collection there were alchemical manuscripts in Newton's hand totaling more than 650,000 words. "They show him to have assimilated the whole corpus of Alchemical Literature and to have been the most learned adept of all time."[10] We know that his library contained all the great works on the subject, including those of Lully, Villanova, Geber and Basil Valentine.

The year 1675 saw Newton's interest turned to electricity, and he sent to the Royal Society a description of an experiment he had made with a glass plate which when rubbed would cause small particles of paper to dance.

The next year, 1676, witnessed the completion of the binomial theorem, on which he had been engaged sporadically since 1669. This work was not officially published until 1704, although it had by that time become quite well known.

The nine years from 1679 to 1687 were the most important in Newton's life, judged by the amount of work he completed. It was in this period that he finished and published his work on gravitation. Wren, Hooke and Halley had become interested in the subject and, although they had glimpses of the truth, they could not formulate a law. In this predicament Halley went to Newton and asked him what course a body would describe if the attraction varied according to the inverse square of the distance. Newton answered that an ellipse would result; he had worked out the problem, but could not find his notes! Halley urged him to repeat the proof, which Newton had recited from memory. The Royal Society became very much interested, and Paget and Halley were appointed to see that Newton kept to his task. This was in 1684. Newton used Picard's figure for the radius of the earth—a figure more accurate than that he had used at Woolsthorpe so many years before—and reconstructed his work. Kepler's second law was established as an undeniable truth. Two more years were given to the problem—1685 and 1686—although Newton at the same time kept on with his teaching and with his chemical work.

The entry in the minute-books of the Royal Society for April 27, 1686, is an interesting one:

> Dr. Vincent presented to the Society a manuscript entitled, *Philosophiae Naturalis principia mathematica*, and dedicated to the society by Mr. Isaac Newton, wherein he gives a mathematical demonstration of the Copernican hypothesis as proposed by Kepler, and makes out all the phenomena of the celestial motions by the only supposition of a gravitation towards the centre of the sun decreasing as the squares of the distances therefrom reciprocally. It was ordered, that a letter of thanks be written to Mr. Newton; and that the printing of this book be referred to the consideration of the council; and that in the meantime the book be put into the hands of Mr. Halley, to make a report thereof to the council.[11]

Halley made his report; he did more before he was done—he took on the burden of seeing the work through the press, and ultimately paid the printer. As President of the Royal Society, Samuel Pepys gave his imprimatur to the work in 1686, and on April 6, 1687, the third book was received.

The seventeenth century in England produced four books that could not well be spared from the libraries of the world. They are the King James Bible, the Shakespeare Folio, *Paradise Lost* and the *Principia*. Lagrange, who was competent to judge, called Newton's work "the greatest production of the human mind."[12] Birkhoff has spoken of it as follows: "This work may justly be regarded as the most important single contribution to physics that has ever been made."[13]

It is not necessary to give here an elaborate analysis of the *Principia*; it is such a fundamental work that its structure and content should be known to all physicists. The crowning feature of

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[10] Sotheby and Co., *Catalogue of the Newton papers*. . . . (London, 1936), p. [iii]. This property was sold on July 13–14, 1936.

[11] More, reference 4, pp. 303–304.

[12] More, reference 4, p. 315.

[13] Birkhoff, "Newton's philosophy of gravitation with special reference to modern relativity ideas," reference 2, p. 56.

the book is the law of gravitation: "Every material particle attracts every other with a force directly proportional to the product of their masses and inversely proportional to the square of the distance between them." Broad declares that there are but two other scientific concepts of sufficient magnitude to compare with this; they are Maxwell's correlation and Einstein's relativity theory.[14]

The chief field of the book is astronomy, although many other branches of science are touched upon. Newton was "the first of all people, to prove that the distant stars, like our sun, are shining by their own light, and not by reflected light."[15] Consider the philosophic importance of that fact: there were other burning worlds besides the sun; there were other bonfires in the infinite. What had lighted them? How long would they burn?

Newton also established that the center of mass of the solar system was not the center of the sun, but a point close to it. He showed that the earth bulges slightly at the equator, thus accounting for the precession of the equinoxes, a phenomenon which had been puzzling men ever since it was first discovered by Hipparchus in 150 B.C.

Before the *Principia* had appeared, comets were frightful portents presaging some terrible calamity—fiery darts of the Almighty's wrath which might in an instant blast the earth into a smoking cinder. Newton changed all this; he showed that comets are subject to the laws of gravitation, and gave a rule for determining their orbits. It is little wonder that Halley, who had worked on the problem, told Voltaire, "It will never be permitted to any mortal to approach nearer to Divinity."[16]

The laws of motion grew out of the work of Galileo, Kepler, Wallis, Wren and Huygens. Galileo had formulated the law of inertia and the principle of the addition of velocities. These two important statements Newton brought into harmony with Kepler's laws, and arrived at his own position: "To every action there is always opposed an equal reaction; or the mutual actions of two bodies upon each other are always equal and opposite."

These proofs were all worked out geometrically. There was little point in using fluxions, for Newton had not shared his discovery, and would have had to educate his readers in the method before they could understand his proofs. As a result, for a century English scientists scorned calculus—which by that time had been developed and published by Leibniz—and laboriously worked out all their problems geometrically.[17]

The *Principia* was no sooner off his mind than Newton plunged into political affairs. This portion of his work shows another side of his extraordinary character. James II tried to force the religious issue by commanding Cambridge to give a degree to a Jesuit, one Father Francis Alban. This was clearly against the statutes; to acquiesce would be tantamount to wrecking the Establishment—to resist would be to incur royal displeasure. What was to be done? A delegation was sent up to London to plead before the illegally reëstablished High Court of Commission, over which the tyrannical Jeffreys presided. Newton was one of the representatives and he appears to have been the Machiavelli of the group. There were few men who could resist the bloody Chief Justice; Newton was one of them. By the sheer force of his personality and the vigor of his cogent arguments, rather than by verbal combats with the judge, he prevented his fellow-members from compromising. The privileges of the University remained, but the attack which James had instituted led the Whig nobility to negotiate with William; Newton thus played a part in bringing about the "Glorious Revolution." All his life he was violently opposed to Catholicism, and among the Portsmouth Papers was an unpublished tract of 7500 words entitled, "A Treatise against the Roman Catholic Church."[18]

It is to be seen, and will become increasingly apparent, that Newton was not one of the Ivory Tower breed of scientists. He took a vital in-

[14] Broad, reference 3, p. 28.

[15] Campbell, "Newton's influence upon the development of astrophysics," reference 2, p. 71.

[16] Pupin, "Newton's dynamics," reference 2, p. 95.

[17] Brown, "Developments following from Newton's work," reference 2, p. 118.

[18] Sotheby, reference 10, lot 259.

terest in public affairs, and in 1689 he represented the University in the Convention Parliament. Here he met Locke, Pepys and the Mashams—all of whom influenced in some measure his later life.

In 1690, Newton's attention centered in Scripture study and theology. He was an untiring exegesist; there were more than 1,250,000 words of theological manuscript in the Portsmouth Collection! The materials show that he was more or less of a Baptist, as Whiston declared, and that his Trinitarianism was not all that it might have been, if, indeed, it existed at all. In addition to theology, he studied ancient chronology, and drew up an elaborate table of dates. These two studies engrossed him during his later years.

For a long time Newton had wished for a government office; his chance came in 1695, when his friend and former student, Charles Montague, secured for him the Wardenship of the Mint.[19]

Newton came to the Mint at a critical time. The state of coinage in England was deplorable. Good money was hoarded, or else melted down and the bullion sold abroad. Clipped coins were very common, and the average value of a shilling had been reduced by half.[20]

Montague's judgment of Newton's ability to handle the situation proved to be well founded. He raised the Mint's average weekly production of silver coins from £15,000 to £120,000. This he accomplished in the midst of a war and without dislocating the financial structure of the country. In the course of his duties, Newton found a way to watermark paper, and a new way to melt down bullion. He also invented several alloys of low fusibility, including one that would melt in a summer sun.[21]

The good judgment and executive ability which Newton had shown as Warden led to his appointment as Master of the Mint in 1699. His interest in alchemy continued, but, as the cataloger of the Portsmouth Collection pointed out:

> After his appointment to the Mint, of course, any open association of his name with Alchemy would have been most indiscreet. The rumour that the Master of the Mint could transmute copper farthings into bright golden guineas would have spread panic through the nations.[22]

In 1701 Newton resigned all of his college posts, and thereby fixed himself in London for the rest of his life. He busied himself with putting his optical papers in order, as well as keeping the Mint working smoothly. In 1703 he was elected President of the Royal Society, a position he held until his death. Flamsteed maintains that although Newton presided, the Society was actually governed by the secretary, Hans Sloane, who covered his own ignorance "by making a bouncing noise."[23]

In 1704, the *Opticks* appeared. Newton had delayed publishing the book until Hooke was dead, thus making sure of avoiding the carping and sniping that inevitably followed any publication in fields which Hooke had staked out as his own. The book was written in the clear, lucid prose of which Newton was a master.

In 1704 Newton also presented to the Royal Society a burning glass he had made; it consisted of an arrangement of seven lenses, and could melt metals and incinerate tile. About this time he also conceived the sextant, but did not construct a model; Hadley rediscovered the principle several years later, and is generally given credit for the invention.

Queen Anne visited Cambridge in 1705, and Newton went up to kneel before her, and was knighted in the Master's Lodge of Trinity. His next few years contain nothing which need detain us, except that they culminated in 1712 in his disgraceful quarrel with Flamsteed. Flamsteed, the Astronomer Royal, had prepared a great catalog of stars. He looked upon this as his own property, and later court decisions proved he was right. Newton took the attitude that the work was government property. After a long series of untoward events, Newton published part of the catalog, and a rather mangled

[19] Montague, later Lord Halifax, was a leading member of the Junto. He had collaborated with Prior in writing the *City mouse and the country mouse*, in reply to Dryden's *Hind and the panther*.

[20] More, reference 4, p. 446.

[21] Newell, "Newton's work in alchemy and chemistry," reference 2, pp. 226 ff.

[22] Sotheby, reference 10, p. [iv].

[23] More, reference 4, p. 535.

edition appeared in 1712, edited by Halley, whom Flamsteed detested. Flamsteed never forgave Newton; he bought up more than 200 of the 300 copies and burned them. His full observations were published after his death, in 1725, under the title *Historia coelestis britannica.* This particular action of Newton's can scarcely be considered as evidence of a universal mind; from Flamsteed's point of view it was simply a compounding of human misery.

In these later years Newton did little creative work in the sciences, although he continued his theological and chronological studies. His attitude towards younger men seems to have been patient and helpful. It was not because he could no longer engage in original research that he left his desk and laboratory; his mind was as sharp as it ever was. This is definitely proved by his astonishing solution of the brachistochrone. He "had forsaken mathematics not because his powers had failed, but because the subject had ceased to interest him."[24]

A second edition of the *Opticks* appeared in 1717. This time, instead of the mathematical appendixes, Newton attached a series of 31 queries, containing many hypothetical questions which he did not wish to include in his strictly empirical writings. The tract *De natura acidorum* appears here—his only publication in chemistry. This does not bear on his alchemical designs, as Sotheby's cataloger points out:

> Although so much of his life was spent in the company of Diana's Doves, chasing the Red and Green Lyons through the Twelve Gates, or elevating Mercury with the full complement of Ten Eagles, he published only one chemical paper . . . and this gave no inkling of the ultimate and magnificent object of his researches.[25]

II

Optics and chemistry were Newton's chief scientific interests. His notion of light has not been completely proved or disproved. He did not try to explain the nature of the phenomenon, or to define its cause, and he was criticized for this. His contemporaries had not grasped the essentials of the empirical method. He was disgusted, and justly so, with these criticisms, and they tended to sour him, making him loath to publish his work.

Newton's theory of light was an indistinct combination of the wave theory and the emission theory. He conceived it to be "fits of easy reflection and easy transmission." But the matter seemed beyond experiment, and he refused to commit himself too deeply. In writing to Hooke, who upheld the wave theory, he said: "It is true that from my theory I argue the corporeity of light, but I do it without any absolute positiveness."[26] Where facts could not be established, he refused to speculate, taking refuge in generalities.

Mathematics never became a fetish with Newton, but was always a tool to be used in solving universal problems. In many cases the tools were of his own invention. In the case of gravitation, Birkhoff says:

> He was the first to triumph over the purely mathematical difficulties involved. In my opinion it is this which constitutes his greatest achievement rather than the first formulation of the law of gravitation, or of the laws of motion, both known by his name today.[27]

His system of fluxions never achieved widespread use, yet it is of importance in the development of the calculus. "The fluxional method achieved purity at the expense of fertility. 'Like a virgin dedicated to God,' to quote Bacon, 'it produced nothing.' "[28]

In the field of astronomy, Newton's work was of paramount importance, as has been seen; the third book of the *Principia* contains his greatest work in this field. He maintained that observatories should be built on mountains; today, most of them are. He showed that we can see more than half of the moon's surface, because the sphere wobbles in its orbit.

Newton's progress in chemistry was limited by the foundations on which he had to build; even though these were limited, he made some progress in the right direction:

> He certainly had pictured in his mind an atomic theory in which the variety of elements was due to the geometrical groupings of a universal atomic substance. He had gone even further in that he queried whether the force which held together, and acted on, those

[24] More, reference 4, p. 571.
[25] Sotheby, reference 10, p. [iv].

[26] More, reference 4, p. 105.
[27] Birkhoff, reference 2, p. 55.
[28] Broad, reference 3, p. 32.

atomic groups were not the same attractive force which bound the planets into a solar system; and he had also queried whether chemical affinity were not a manifestation of electricity.[29]

In thermometry, Newton invented a linseed oil instrument which scaled 32°F at 0, and used 98.5°F as 12. With this rather crude tool he established the law of cooling: he also showed that "when a body is melting or evaporating, its temperature remains constant."[30] In combustion, Lavoisier later proved Newton to be correct in rejecting the idea of "ponderable substance" as a component of fire.

The scope of the man's interest was immense. He dissected sheep's eyes and studied the problem of binocular sight. He was interested in calendar reform; he tried to construct an artificial language.[31] In agriculture, as befitted the lord of a manor, he tried to find out what kind of apple tree was best suited to Cambridgeshire—he wished to improve the local cider. As a calculator, he bettered the slide rule by showing "how to solve numerical cubic equations mechanically with the aid of three Gunter scales."[32] He made no contribution to medical knowledge except by example; when he had a cold he went to bed for several days.

Perhaps considered from the standpoint of historical science, Newton's greatest contribution was in establishing the scientific method of inductive reasoning. William Gilbert had practiced it; Bacon had proposed its universal acceptance; Galileo, Kepler and Descartes had followed it with varying degrees of faithfulness. But Newton was the first really to fight for it.

Cartesian hypothesis was fashionable at the time, and Newton found his contemporaries unable to make a clear distinction between hypothetical reasoning and empiricism.[33] He took his stand for experimental law; it was a new trend, but it caught on quickly. Boyle, Sydenham and Locke took a dislike to speculation when it intruded into scientific problems, and it was the hierarchy of Bacon, Newton and Locke that was instrumental in making empiricism and science synonymous. Newton's own words tell the story: "The proper method for enquiring after the properties of things is to deduce them from experiments."[34] With superb scorn, he uttered that famous dictum, "Hypotheses non fingo"—"I do not concern myself with hypotheses."

Snow[35] shows that this was not literally true. Newton did think that hypothesis had a definite place, but it was not a primary factor in the development of scientific truth. Hypothesis entered after experimentation had proceeded as far as possible; if further experimentation bore out a hypothesis formed from the first set of facts, a theory had been established, and from that a universal law could be formulated. In the General Scholium to the *Principia*, these views are made clear.

Newton's daring imagination, always panting to get to the very heart of things, was sternly held in check by an uncompromising sense of fact.

> True science to him, and ultimately the idea must be accepted by all of us, is restricted to the world of the finite in space, time, and substance; both the infinitely large and the infinitely small are inaccessible to discovery through our sense perceptions and by science.[36]

By expanding "science" to its original sense—that of *knowing*—we may be justified in considering some of the philosophic aspects of Newton's work. The motto on his bookplate was "Philosophemur"—"Let us philosophize!" The tremendous labors he made in the service of science were undertaken in this spirit. He believed that "the chief value of his scientific work lay in its support of revealed religion."[37] "While the world will always regard his scientific work as an end in itself, he seems to have felt it was a hard and dreary taskmaster, and not of intrinsic value except as it should give evidence of the laws and attributes of God."[38] That is but one more contradiction in the Newtonian chronicle—the facts which have sometimes been marshaled to prove the sheer mechanistic nature of the universe were originally searched out in order to glorify the Creator!

[29] More, reference 4, p. 165.
[30] Newell, reference 2, p. 223.
[31] Sotheby, reference 10, lot 313.
[32] Wolf, *A history of science, technology, and philosophy in the 16th and 17th centuries* (Macmillan, 1935), p. 560.
[33] More, reference 4, p. 105.
[34] Wolf, reference 32, p. 671.
[35] Snow, *Matter and gravity in Newton's physical philosophy* (Oxford Univ. Press, 1926), pp. 230 ff.
[36] More, reference 4, p. 379.
[37] More, reference 4, p. 608.
[38] More, reference 4, p. 609.

Wolf believes that Newton's ideas tended toward mechanism; this is more to be seen in the development of Newton's theories in later years than in his own statement of them.[39] Samuel Clarke, in his brilliant defense of Newtonianism against the attack of the Leibnizian mechanistic conception of a clock-work universe in which the sun cries "Cuckoo!" every morning and the weights are somehow pulled up by an unseen counterbalance, explained his master's views on the possible nature of gravitation in these words: "The means by which two bodies attract each other may be *invisible* and intangible, and of a different nature from *mechanism;* and yet acting regularly and constantly, may well be called natural."[40]

This may seem to be a somewhat vague and colorless defense, but it is the only logical defense, and Newton was not one to paint his views in striking colors merely that they might attract more attention; nor did Clarke have that kind of mind. Bentley's Boyle lectures developed the same thought, and Newton approved of them, realizing of course that neither he nor Bentley nor Clarke was talking science; they were talking not physics, but metaphysics.

It is only natural that Newton's philosophical tendencies should have been those of the Cambridge of his day. Henry More was one of his friends, and came from the same grammar school. It is not startling to learn, therefore, that Newton made the same distinction between matter and form as did the Cambridge Platonists: matter was substance—form was an ineffable effluvium. Gilbert and Boyle made the same distinction; it had first been made by Aristotle.[41] Henry More used gravitation as a proof of the unity of Nature, and so declared in his *Antidote against atheism* and his *Immortality of the soul.*[42] Newton himself had somewhat the same idea, and conceived that God was the soul of the world —"anima mundi"—but that He dominated the universe in all things. "God and His divine sensorium are the same."[43]

Newton's chief service, E. W. Brown declares, was to teach mankind how to predict the future.[44] Adams and Leverrier ascertained, by means of the intellectual tools which Newton had forged and tempered, that another world exists, and by observing the irregularities in the orbit of Uranus, told men where to look to see Neptune.

Isaac Newton was blessed with a universal mind; consider for a moment the fields in which he achieved distinction: he was a physicist, astronomer, mathematician, teacher, public servant, lawmaker, metallurgist, chemist, geographer, chronologist, theologian, craftsman and philosopher.

Although his work has often been admired uncritically, it has never been overestimated as a landmark in human thought. In the *Rambler* (No. 83), Samuel Johnson wrote: "To hew stone, would have been unworthy of Palladio; and to have rambled in search of shells and flowers, had but ill suited with the capacity of Newton." And yet, shortly before he died, Newton with touching humility declared: "I do not know what I may appear to the world; but to myself I seem to have been only like a boy, playing on the sea-shore . . . whilst the great ocean of truth lay all undiscovered before me."

[39] Wolf, reference 32, p. 673.
[40] Snow, reference 35, p. 207.
[41] Snow, reference 35, p. 182.
[42] Snow, reference 35, p. 195.
[43] Snow, reference 35, pp. 208–210.
[44] Brown, reference 2, p. 113.

SCIENCE is not formal logic—it needs the free play of the mind in as great a degree as any other creative art. It is true that this is a gift which can hardly be taught, but its growth can be encouraged in those who already possess it.—MAX BORN.

Newton's Third Law and Electrodynamics

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NEWTON'S three laws of motion form the basis of all our ideas of mechanics and hence are at the very foundation of the science—or sciences—of physics; and conservation of momentum and of angular momentum of isolated systems, which these laws imply, are principles to which we can cling most firmly, when other details of a problem may be in doubt. The three laws form a unified whole; the violation of any one would imply violation of the conservation of momentum. For example, if the third law were not true for some systems, the forces between the particles making up that system would imply changes of momentum of the particles, in such a way that the momentum of the whole system would be altered, even in the absence of forces acting on the system from outside. So any attempt to invalidate the third law must be "viewed with alarm," and examined critically.

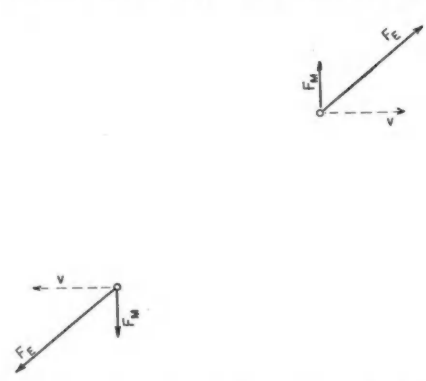

FIG. 1. Charged particles moving with constant speeds in opposite directions along parallel paths exert on each other electric forces F_E and magnetic forces F_M, as shown. The resultants are equal in magnitude but do not act along the same line, in apparent violation of the law of action and reaction.

Nevertheless, many people have from time to time called attention to a class of phenomena in which Newton's third law seems not to hold—namely, when electromagnetic forces are involved. We mention two particular examples of this. The first is that of two equally charged bodies having velocities which are equal in magnitude and opposite in direction (Fig. 1). Besides the electrostatic force of repulsion F_E between them, which acts along the line connecting the instantaneous positions of the two charges, there is an additional force F_M acting on each charge. This is a magnetic force, which arises because a moving charge is essentially a current element. The magnetic forces acting on the two charges are equal in magnitude, owing to the symmetry of the problem, but they do not act along a common line!

The second example[2] is that of two equally charged bodies moving at right angles to each other (Fig. 2). If one considers the moving charges as current elements, it is evident that at the instant the second charge is passing the (extended) trajectory of the first, the magnetic field of the second charge exerts a force on the first charge, while the latter is in no position to influence the former magnetically.[3]

In both of these examples, if there are no external forces, the individual charges will be accelerated by the electromagnetic forces, in accordance with Newton's second law, but the total momentum or angular momentum of the pair of charges will be changing; or, if external forces are applied to balance the electromagnetic forces, and hence prevent acceleration, there will be no change in momentum of the pair of charges, even though the sum of the external forces applied is different from zero.

The resolution of this dilemma is not new. The magnetic forces between two moving charges as well as the corrections to the electrostatic forces are of order $(v/c)^2$ compared to the electrostatic forces. Here v represents the mean velocity of the charges, and c is the velocity of light. Now

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[2] S. B. L. Mathur, Phil. Mag. **32**, 171 (1941).

[3] Actually, this is somewhat of an oversimplification. The purely repulsive forces which act on the two charges are not exactly equal in magnitude, as can be seen from the precise expressions for the forces, Eqs. (4) and (5).

electrodynamic effects are propagated with a finite velocity c. The "retardation," or finite time of propagation, introduces corrections in the forces of order $(v/c)^2$ and hence must be taken into account if one is interested in the magnetic forces. This sounds as if we might hope for the validity of a modified third law, in which momentum is averaged in some way over time. Actually, one can restore the third law to complete respectability and validity by introducing the artifice of the "electromagnetic field" to which one attributes a momentum density[4] $(1/4\pi c)(\mathbf{E}\times\mathbf{H})$, where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field strengths, in Gaussian units. The "field" has just as much claim to *reality* as the original concept of momentum. Momentum is transferred from a charge to the field, through the field, and perhaps to other charges.

The apparent failure of Newton's third law to apply to the system of two charged bodies can now be explained by saying that the system considered must consist not only of the two charges, but also of the field. In the absence of external forces, the constancy of the total momentum of the system, charges-plus-field, is an assumption that can be defended, whereas without introducing the field this is not the case. If external forces are present, the vector sum of the forces will give the time-rate of change of the total momentum. The corresponding statements about torques and angular momenta are also correct.

The truth of these statements is a consequence of the Maxwell equations of electrodynamics. But it seems of interest actually to carry out the calculation and show that, when the momentum of the field is taken into account, Newton's laws are fulfilled. We propose to carry through the calculations for the second afore-mentioned example. The case of parallel motion of the charges is somewhat simpler, and can be carried through in just the same way.

To make the problem definite, we will consider two particles of charge e, moving along the x and y axes with velocities v_1 and v_2, respectively. To maintain this uniform motion, we will supply whatever (nonelectric) forces are required. These forces will of course just balance the electromagnetic forces on the two charges; and the sum of these forces should be equal to the time-rate of change of the momentum in the field, since the momenta of the charges do not change.

The fields produced at any point (x, y, z) by a particle of charge e moving with a constant velocity v in the x direction and located instantaneously at the origin, are given by[5]

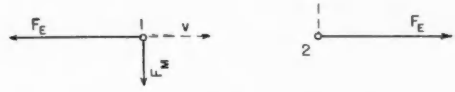

FIG. 2. Another apparent violation of Newton's third law. Particle *1* experiences a force F_M due to the magnetic field set up by particle *2*, but *1* cannot exert any magnetic force upon particle *2*.

$$\left.\begin{aligned} E_x&=[1-(v/c)^2]^{-\frac{1}{2}}(ex/R^3),\\ E_y&=[1-(v/c)^2]^{-\frac{1}{2}}(ey/R^3),\\ E_z&=[1-(v/c)^2]^{-\frac{1}{2}}(ez/R^3),\end{aligned}\right\}\quad(1)$$

$$\left.\begin{aligned} H_x&=0,\\ H_y&=-[1-(v/c)^2]^{-\frac{1}{2}}(v/c)(ez/R^3),\\ H_z&=[1-(v/c)^2]^{-\frac{1}{2}}(v/c)(ey/R^3),\end{aligned}\right\}\quad(2)$$

where

$$R^2\equiv x^2/[1-(v/c)^2]+y^2+z^2. \quad (3)$$

At the time t, the coordinates of the two charges will be $(v_1t-a, 0, 0)$ and $(0, v_2t, 0)$, respectively. At the instant $t=0$, the charges will be in the position indicated in Fig. 2. Then, by Eqs. (1) and (2), the electromagnetic force on particle *1* at any time is

$$\left.\begin{aligned} F_{1x}&=\left[1-\left(\frac{v_2}{c}\right)^2\right]^{-\frac{1}{2}}\frac{e^2(v_1t-a)}{Q_1^3},\\ F_{1y}&=\left[1-\left(\frac{v_2}{c}\right)^2\right]^{-\frac{1}{2}}\\ &\qquad\times\left[-\frac{e^2v_2t}{Q_1^3}+\frac{v_1v_2}{c^2}\frac{e^2(v_1t-a)}{Q_1^3}\right],\\ F_{1z}&=0;\end{aligned}\right\}\quad(4)$$

[4] M. Abraham, Ann. d. Physik **10**, 105 (1903); or see, for example, Page and Adams, *Principles of electricity* (Van Nostrand, 1936), p. 579.

[5] See, for example, Mason and Weaver, *The electromagnetic field* (Univ. of Chicago Press, 1929), p. 298.

and that on particle *2* is

$$\left.\begin{aligned}
F_{2x}&=\left[1-\left(\frac{v_1}{c}\right)^2\right]^{-\frac{1}{2}}\\
&\qquad\times\left(-\frac{e^2(v_1t-a)}{Q_2^3}+\frac{v_1v_2}{c^2}\frac{e^2v_2t}{Q_2^3}\right),\\
F_{2y}&=\left[1-\left(\frac{v_1}{c}\right)^2\right]^{-\frac{1}{2}}\frac{e^2v_2t}{Q_2^3},\\
F_{2z}&=0.
\end{aligned}\right\}\tag{5}$$

Here we have set

$$\left.\begin{aligned}
Q_1^2&\equiv(v_1t-a)^2+\frac{(v_2t)^2}{1-(v_2/c)^2},\\
Q_2^2&\equiv\frac{(v_1t-a)^2}{1-(v_1/c)^2}+(v_2t)^2.
\end{aligned}\right\}\tag{6}$$

At any point in space, the electric and magnetic fields are the vector sums of the respective fields due to each charge separately. We may indicate this by suitable subscripts. Then the momentum density $\mathbf{m}$ will be given by

$$\begin{aligned}
\mathbf{m}&=(1/4\pi c)[(\mathbf{E}_1+\mathbf{E}_2)\times(\mathbf{H}_1+\mathbf{H}_2)]\\
&=(1/4\pi c)\{[\mathbf{E}_1\times\mathbf{H}_1]+[\mathbf{E}_2\times\mathbf{H}_2]\\
&\qquad+[\mathbf{E}_1\times\mathbf{H}_2]+[\mathbf{E}_2\times\mathbf{H}_1]\}\\
&=\mathbf{m}_1+\mathbf{m}_2+\mathbf{m}_{12}.
\end{aligned}$$

The integrals of $\mathbf{m}_1$ and $\mathbf{m}_2$ over all space are functions only of v_1 and v_2, respectively, and hence will not change if no acceleration is allowed. Hence we need only calculate the part $\mathbf{M}$ of the total momentum that is due to $\mathbf{m}_{12}$, namely,

$$\mathbf{M}=\int\mathbf{m}_{12}dV.$$

We write the separate components of $\mathbf{M}$ as follows:

$$\left.\begin{aligned}
M_x&=\frac{e^2}{4\pi c}\left[1-\left(\frac{v_1}{c}\right)^2\right]^{-\frac{1}{2}}\\
&\qquad\times\left[1-\left(\frac{v_2}{c}\right)^2\right]^{-\frac{1}{2}}\int\frac{dV}{R_1^3R_2^3}\\
&\qquad\times\left\{\left(\frac{v_1}{c}\right)[y(y-v_2t)+z^2]-\frac{v_2}{c}xy\right\},\\
M_y&=\frac{e^2}{4\pi c}\left[1-\left(\frac{v_1}{c}\right)^2\right]^{-\frac{1}{2}}\\
&\qquad\times\left[1-\left(\frac{v_2}{c}\right)^2\right]^{-\frac{1}{2}}\int\frac{dV}{R_1^3R_2^3}\\
&\qquad\times\left\{-\frac{v_1}{c}xy+\frac{v_2}{c}[x(x-v_1t+a)+z^2]\right\},\\
M_z&=\frac{e^2}{4\pi c}\left[1-\left(\frac{v_1}{c}\right)^2\right]^{-\frac{1}{2}}\\
&\qquad\times\left[1-\left(\frac{v_2}{c}\right)^2\right]^{-\frac{1}{2}}\int\frac{dV}{R_1^3R_2^3}\\
&\qquad\times\left\{-\frac{v_1}{c}xz-\frac{v_2}{c}yz\right\}=0,
\end{aligned}\right\}\tag{7}$$

where

$$\left.\begin{aligned}
R_1^2&\equiv\frac{(x-v_1t+a)^2}{1-(v_1/c)^2}+y^2+z^2,\\
R_2^2&\equiv x^2+\frac{(y-v_2t)^2}{1-(v_2/c)^2}+z^2.
\end{aligned}\right\}\tag{8}$$

The writer was unable to evaluate these integrals exactly. However, the calculations can be carried out for low velocities. One can expand the expressions for the forces in powers of v/c. As was previously mentioned, the terms independent of v/c in the expressions for the forces on the two charges are equal and opposite, and hence cancel. We are interested primarily in the terms of order $(v/c)^2$. If we calculate the momentum of the field to the lowest order of v/c, the time derivative of this lowest order term should just correspond to the terms of order $(v/c)^2$ in the force expressions. This approximation is equivalent to dropping all factors $1-(v_1/c)^2$ or $1-(v_2/c)^2$ in Eqs. (7) and (8). The resulting integrals are not difficult to evaluate.

Let us introduce the new coordinates,

$$\left.\begin{aligned} X&=\frac{v_1t-a}{S}\left(x-\frac{v_1t-a}{2}\right)-\frac{v_2t}{S}(y-\tfrac{1}{2}v_2t),\\ Y&=\frac{v_2t}{S}\left(x-\frac{v_1t-a}{2}\right)+\frac{v_1t-a}{S}(y-\tfrac{1}{2}v_2t),\end{aligned}\right\}\tag{9a}$$

or

$$\left.\begin{aligned} x&=\frac{v_1t-a}{S}(X+\tfrac{1}{2}S)+\frac{v_2t}{S}Y,\\ y&=-\frac{v_2t}{S}(X-\tfrac{1}{2}S)+\frac{v_1t-a}{S}Y,\end{aligned}\right\}\tag{9b}$$

where

$$S^2\equiv(v_1t-a)^2+(v_2t)^2.\tag{10}$$

In terms of these new coordinates,

$$(x-v_1t+a)^2+y^2+z^2=(X-\tfrac{1}{2}S)^2+Y^2+z^2,$$

$$x^2+(y-v_2t)^2+z^2=(X+\tfrac{1}{2}S)^2+Y^2+z^2.$$

The denominators of all the integrands in the expressions for momentum [Eq. (7)]—in the low velocity approximation—become

$$[(X-\tfrac{1}{2}S)^2+Y^2+z^2]^{\frac{3}{2}}[(X+\tfrac{1}{2}S)^2+Y^2+z^2]^{\frac{3}{2}}\equiv D,$$

while the numerators are still quadratic expressions in X, Y and z. These integrals can be reduced to three types:

I. Integrals in which the numerator is linear in X or Y; these integrals vanish because the integrands are odd functions of X or Y.

II. $$\int\frac{X-\frac{1}{4}S^2}{D}dV=0.$$

III. $$\int(Y^2/D)dV=\int(z^2/D)dV=2\pi/S.$$

The evaluations of integrals II and III are carried out in the appendix.

Thus we obtain

$$\left.\begin{aligned} M_x&=\frac{e^2}{2c^2S}\left\{v_1\left[\left(\frac{v_1t-a}{S}\right)^2+1\right]-v_2\frac{v_2t(v_1t-a)}{S^2}\right\},\\ M_y&=\frac{e^2}{2c^2S}\left\{-v_1\frac{v_2t(v_1t-a)}{S^2}+v_2\left[\left(\frac{v_2t}{S}\right)^2+1\right]\right\}.\end{aligned}\right\}\tag{11}$$

Differentiating these expressions with respect to time we obtain, after some simplification,

$$\begin{aligned} \frac{dM_x}{dt}&=\frac{e^2}{S^3}\left\{\frac{1}{2}\frac{v_1^2-v_2^2}{c^2}(v_1t-a)-\frac{v_1v_2}{c^2}v_2t-\frac{3}{2}\frac{v_1t-a}{S^2}\right.\\ &\qquad\left.\times\left[\left(\frac{v_1}{c}\right)^2(v_1t-a)^2-\left(\frac{v_2}{c}\right)^2(v_2t)^2\right]\right\},\\ \frac{dM_y}{dt}&=\frac{e^2}{S^3}\left\{\frac{1}{2}\frac{v_2^2-v_1^2}{c^2}v_2t-\frac{v_1v_2}{c^2}(v_1t-a)+\frac{3}{2}\frac{v_2t}{S^2}\right.\\ &\qquad\left.\times\left[\left(\frac{v_1}{c}\right)^2(v_1t-a)^2-\left(\frac{v_2}{c}\right)^2(v_2t)^2\right]\right\}.\end{aligned}\tag{12}$$

We wish to compare these quantities with the terms of order $(v/c)^2$ in the expressions for the forces on the charged particles. In the x direction, the sum of the electromagnetic forces on the charges is

$$\begin{aligned} F_x&=\frac{e^2}{S^3}\left\{\frac{1}{2}\left(\frac{v_2}{c}\right)^2(v_1t-a)-\frac{3}{2}\left(\frac{v_2}{c}\right)^2\frac{(v_2t)^2}{S^2}(v_1t-a)-\frac{1}{2}\left(\frac{v_1}{c}\right)^2\right.\\ &\qquad\left.\times(v_1t-a)+\frac{3}{2}\left(\frac{v_1}{c}\right)^2\frac{(v_1t-a)^3}{S^2}+\frac{v_1v_2}{c^2}v_2t\right\}\\ &=\frac{e^2}{S^3}\left\{\frac{1}{2}\frac{v_2^2-v_1^2}{c^2}(v_1t-a)+\frac{v_1v_2}{c^2}v_2t+\frac{3}{2}\frac{v_1t-a}{S^2}\right.\\ &\qquad\left.\times\left[\left(\frac{v_1}{c}\right)^2(v_1t-a)^2-\left(\frac{v_2}{c}\right)^2(v_2t)^2\right]\right\},\end{aligned}\tag{13}$$

to the approximation being considered. Likewise, the sum of the electromagnetic forces in the y

direction is given by

$$F_y=\frac{e^2}{S^3}\left\{-\frac{1}{2}\left(\frac{v_2}{c}\right)^2 v_2t+\frac{3}{2}\left(\frac{v_2}{c}\right)^2\frac{(v_2t)^3}{S^2}+\frac{v_1v_2}{c^2}(v_1t-a)+\frac{1}{2}\left(\frac{v_1}{c}\right)^2 v_2t-\frac{3}{2}\left(\frac{v_1}{c}\right)^2\frac{(v_1t-a)^2}{S^2}v_2t\right\}$$
$$=\frac{e^2}{S^3}\left\{\frac{1}{2}\frac{v_1^2-v_2^2}{c^2}v_2t+\frac{v_1v_2}{c^2}(v_1t-a)-\frac{3}{2}\frac{v_2t}{S^2}\times\left[\left(\frac{v_1}{c}\right)^2(v_1t-a)^2-\left(\frac{v_2}{c}\right)^2(v_2t)^2\right]\right\}. \tag{14}$$

A comparison of these expressions with Eq. (12) shows that

$$F_x=-dM_x/dt,\quad F_y=-dM_y/dt.$$

The negative sign here is correct, as it must be recalled that the external (nonelectric) forces are opposite in direction to the electromagnetic forces.

To complete the job, we should calculate the angular momenta of the field about a set of orthogonal axes and show that the time derivative of the angular momentum about each axis equals the torque about that axis. The angular momentum of the field about any axis is obtained by multiplying the momentum density at each point by the proper lever arm and integrating the result over all space. Again, of the total momentum density,

$$\mathbf{m}=\mathbf{m}_1+\mathbf{m}_2+\mathbf{m}_{12},$$

we need only concern ourselves with $\mathbf{m}_{12}$, as that part of the angular momentum due to $\mathbf{m}_1$ and $\mathbf{m}_2$ does not vary with time. If we choose for axes the three coordinate axes, the angular momenta about the x and y axes are zero, while that about the z axis is

$$N_z=\int(xm_{12y}-ym_{12x})dV$$
$$=\frac{e^2}{4\pi c}\left[1-\left(\frac{v_1}{c}\right)^2\right]^{-\frac{1}{2}}\left[1-\left(\frac{v_2}{c}\right)^2\right]^{-\frac{1}{2}}\times\int\frac{dV}{R_1^3R_2^3}\cdot\left\{-\frac{v_1y}{c}[x^2+y(y-v_2t)+z^2]+\frac{v_2x}{c}[x(x-v_1t+a)+y^2+z^2]\right\}.$$

The angular momentum can be calculated to the same approximation as was the linear momentum —by neglecting terms of order $(v/c)^2$ compared to unity. This is done by using the same transformation as before, namely, Eq. (9). The same integrals occur, and so the result is readily obtained:

$$N_z=\frac{e^2}{2cS}\left\{-\frac{v_1}{c}\left[v_2t+\frac{(v_1t-a)^2v_2t}{S^2}\right]+\frac{v_2}{c}\left[v_1t-a+\frac{(v_1t-a)(v_2t)^2}{S^2}\right]\right\}$$
$$=\frac{e^2}{2cS}\left\{-\frac{v_1}{c}v_2t+\frac{v_2}{c}(v_1t-a)-\frac{(v_1t-a)v_2t}{S^2}\left[\frac{v_1}{c}(v_1t-a)-\frac{v_2}{c}v_2t\right]\right\}, \tag{15}$$

whence

$$\frac{dN_z}{dt}=\frac{e^2}{S^3}\left\{\frac{1}{2}\frac{v_2^2-v_1^2}{c^2}(v_1t-a)v_2t+\frac{v_1v_2}{c^2}[(v_2t)^2-(v_1t-a)^2]+\frac{3}{2}\frac{(v_1t-a)v_2t}{S^2}\times\left[\left(\frac{v_1}{c}\right)^2(v_1t-a)^2-\left(\frac{v_2}{c}\right)^2(v_2t)^2\right]\right\}. \tag{16}$$

We have to compare this expression with that for the torque exerted by the external forces on the charged particles, namely,

$$L_z=-(v_1t-a)F_{1y}+(v_2t)F_{2x}. \tag{17}$$

If terms in v/c of order higher than $(v/c)^2$ are neglected, this becomes

$$L_z=\frac{e^2}{S^3}\left\{-(v_1t-a)\left[-\frac{1}{2}\left(\frac{v_2}{c}\right)^2 v_2t\right.\right.$$
$$\left.+\frac{3}{2}\left(\frac{v_2}{c}\right)^2\frac{(v_2t)^3}{S^2}+\frac{v_1v_2}{c^2}(v_1t-a)\right]$$
$$+v_2t\left[-\frac{1}{2}\left(\frac{v_1}{c}\right)^2(v_1t-a)\right.$$
$$\left.\left.+\frac{3}{2}\left(\frac{v_1}{c}\right)^2\frac{(v_1t-a)^3}{S^2}+\frac{v_1v_2}{c^2}v_2t\right]\right\} \quad (18)$$
$$=\frac{e^2}{S^3}\left\{\frac{1}{2}\frac{v_2{}^2-v_1{}^2}{c^2}(v_1t-a)v_2t\right.$$
$$+\frac{v_1v_2}{c^2}[(v_2t)^2-(v_1t-a)^2]+\frac{3}{2}\frac{(v_1t-a)v_2t}{S^2}$$
$$\left.\times\left[\left(\frac{v_1}{c}\right)^2(v_1t-a)^2-\left(\frac{v_2}{c}\right)^2(v_2t)^2\right]\right\},$$

and we find that L_z, the applied torque, is identical with dN_z/dt, the time-rate of increase of angular momentum.

So we see that, to the order of approximation employed here, inclusion of the momentum of the electromagnetic field gives results completely in accord with Newton's laws, whereas neglect of the field results in serious difficulties.

APPENDIX

The integrals II and III of the text are readily evaluated in terms of confocal elliptical coordinates,

$$X=\tfrac{1}{2}S\lambda\mu,$$
$$Y=\tfrac{1}{2}S(\lambda^2-1)^{\frac{1}{2}}(1-\mu^2)^{\frac{1}{2}}\cos\vartheta,$$
$$z=\tfrac{1}{2}S(\lambda^2-1)^{\frac{1}{2}}(1-\mu^2)^{\frac{1}{2}}\sin\vartheta.$$

The volume element becomes $(\lambda^2-\mu^2)d\lambda d\mu d\vartheta$, and the range of integration is

$$1<\lambda<\infty,$$
$$-1<\mu<1,$$
$$0<\vartheta<2\pi.$$

$$\text{II.}\quad \int\frac{X-\frac{1}{4}S^2}{D}dV=\frac{2}{S}\int\frac{\lambda^2\mu^2-1}{(\lambda^2-\mu^2)^2}d\lambda d\mu d\vartheta$$
$$=\frac{4\pi}{S}\int_1^\infty d\lambda\int_{-1}^{1}\frac{\lambda^2\mu^2-1}{(\lambda^2-\mu^2)^2}d\mu$$
$$=\frac{4\pi}{S}\int_1^\infty d\lambda\left[\frac{\lambda^4-1}{2\lambda^2}\frac{\mu}{\lambda^2-\mu^2}-\frac{\lambda^4+1}{4\lambda^3}\ln\frac{\lambda+\mu}{\lambda-\mu}\right]_{\mu=-1}^{1}$$
$$=\frac{4\pi}{S}\int_1^\infty\left(\frac{\lambda^2+1}{\lambda^2}-\frac{\lambda^4+1}{2\lambda^3}\ln\frac{\lambda+1}{\lambda-1}\right)d\lambda$$
$$=\frac{4\pi}{S}\left[\frac{\lambda^2-1}{2\lambda}-\frac{\lambda^4-1}{4\lambda^2}\ln\frac{\lambda+1}{\lambda-1}\right]_1^\infty=0.$$

$$\text{III.}\quad \int(Y^2/D)dV=\frac{2}{S}\int\frac{(\lambda^2-1)(1-\mu^2)}{(\lambda^2-\mu^2)^2}\cos^2\vartheta d\lambda d\mu d\vartheta$$
$$=\frac{2\pi}{S}\int_1^\infty(\lambda^2-1)d\lambda\int_{-1}^{1}\frac{1-\mu^2}{(\lambda^2-\mu^2)^2}d\mu$$
$$=\frac{2\pi}{S}\int_1^\infty(\lambda^2-1)d\lambda\left[-\frac{\lambda^2-1}{2\lambda^2}\frac{\mu}{\lambda^2-\mu^2}+\frac{\lambda^2+1}{4\lambda^3}\ln\frac{\lambda+\mu}{\lambda-\mu}\right]_{\mu=-1}^{1}$$
$$=\frac{2\pi}{S}\int_1^\infty(\lambda^2-1)\left(\frac{\lambda^2+1}{2\lambda^3}\ln\frac{\lambda+1}{\lambda-1}-\frac{1}{\lambda^2}\right)d\lambda$$
$$=\frac{2\pi}{S}\left[\left(\frac{\lambda^2-1}{2\lambda}\right)^2\ln\frac{\lambda+1}{\lambda-1}-\frac{\lambda^2+1}{2\lambda}\right]_1^\infty=\frac{2\pi}{S}.$$

Physics at the Worcester Polytechnic Institute

MORTON MASIUS
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THE Worcester Polytechnic Institute—hereinafter called W.P.I.—is a small New England college. It is kept small by limiting admission to the freshman class to 180 men in any one year. With the exception of a rather small number of students who concentrate their studies in the fields of either chemistry or physics, all undergraduates expect to take their degree of bachelor of science in some branch of engineering. In the following outline, the general course in physics—a required subject for all students—will be discussed first, then the special courses for students who expect to take their degree in physics, then building and equipment, and last, a brief history of the department.

THE GENERAL COURSE

Instruction in physics begins in the first term of the freshman year. The subject matter of Physics 1 consists of statics, kinematics, dynamics and the properties of fluids. This is followed in the second term of the freshman year by Physics 2, on harmonic motion, waves, sound and heat. In the first term of the sophomore year, students take Physics 3, electricity and magnetism, and in the second term Physics 4, light and selected topics from modern physics.

The time allowed per week is two lectures, two recitations and one two-hour laboratory period throughout the freshman year; and two lectures, two recitations, one three-hour laboratory period

and one extra hour, which is devoted to discussion of the laboratory work and an introduction to the theory of errors, in the sophomore year.

The features of this course that will be of most interest to teachers of physics are: the relation of physics to mathematics; the different types of laboratory exercises and the part they play in the instructional scheme; and some points of a purely pedagogic nature.

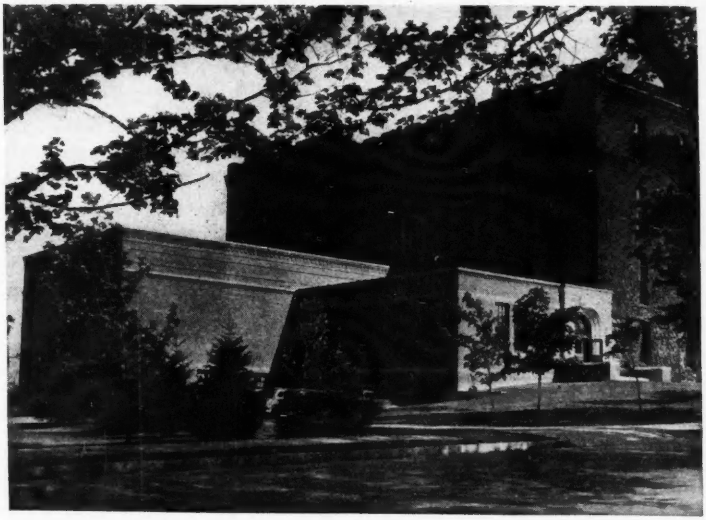
The required mathematics courses are given throughout the freshman and sophomore years; the time allowed is five recitations per week in the freshman year and three recitations per week in the sophomore year. Instead of following the formerly common order of college algebra, analytic geometry, differential calculus and integral calculus, which would put the continuity concept and the derivative in the latter part of the freshman year and the sum of infinitesimals and definite integral in the sophomore year, the order is changed so as to introduce these important ideas as soon as possible. Trigonometry and solid geometry are required for entrance to W.P.I. However, at the start of the mathematics course, there is a review of trigonometry with a few examples for computation. This review fits very well with the beginning of statics, the addition and resolution of forces. It might seem that this is an objectionable duplication, the same subject being taught simultaneously in both the mathematics and physics departments. A slight duplication it may be, but not an objectionable one. The sooner the freshman realizes that he is not to study separate courses, each isolated from all others, but to aim at acquisition of knowledge as a whole, the better off he will be. Surely the teaching of mathematics is strengthened if the student does not learn his mathematics as a subject *per se* but uses it at once in classroom and laboratory; and the teaching of physics is certainly more economical and more effective if the instructor can rely on a reasonable familiarity with the notion of component, the law of cosines, and so forth.

It should not be thought, however, that the entire teaching program of mathematics and physics is subordinated to the idea of providing concurrent instruction by both departments in the most important concepts. It is well known to physics teachers that in the survey course in physics alone there is no one best order. The attempt to coordinate physics and mathematics to produce concurrent teaching creates the "best order" for both subjects as measured by this criterion, but a very poor order, especially in mathematics, when judged by other criterions. It is, therefore, reasonable cooperation that is sought rather than forced cooperation, forced by a supposed compulsory order of presentation.

The concept of rates is reached in physics and mathematics at about the same time; probably the physics course is ahead by a few recitations. The fact, discovered by Galileo, that spheres roll down an inclined plane in such a way that the distance is proportional to the square of the time is interpreted in the physics course in the customary manner using the speed graph, essentially due to Galileo himself, and yields the conclusion that the speeds in this case are proportional to the time and that the acceleration is constant. It is also emphasized that Galileo had to go to considerable trouble, because he did not have the mathematical tools, discovered after his death, but now available even to freshmen, if they care to learn. Then, in the mathematics course, after differentiation of $y=kx^2$, the time-rates of change both of distance and speed are studied from $s=kt^2$.

At a later stage, namely, at the point where the rotational inertia of a body has to be calculated, the physics course is again ahead of the mathematics, for at this stage—about the eleventh week of Physics 1—Mathematics 1 has not yet reached the definite integral. The concept of the limit of a sum of infinitesimals is thus first presented to the student in the physics course. However, only one example of such a limit of a sum—that of the rotational inertia of a rod—is worked out by an algebraic method. For the rest, the student is given a table of the values of I for the most important cases, and the calculus proofs are omitted for the time, to be taken up at length and in detail by the department of mathematics at the point where good illustrations of the operation of evaluating limits of sums by integration are required.

The treatment of harmonic motion is another point where physics and mathematics consider the same topic and where the mathematics should be ahead but is not. At the stage where



The Salisbury building. The larger addition contains the large lecture room.

the differentiation and integration of trigonometric forms are required in physics, at the beginning of the second term, the student does not handle them with sufficient ease, since, in the attempt to introduce him promptly to the important notions of the derivative and of the integral, regarded both as antidifferential and as sum, the earlier illustrative examples have been taken from simple algebraic functions.

Thereafter the mathematics is always ahead. The work done by an expanding gas, the potential difference of two points in a field, the field near a straight conductor, the use of differentials instead of small quantities in error calculation, and the many other cases where a knowledge of calculus is desirable for the physics student are all well taken care of.

Laboratory instruction has received much attention at W.P.I. To judge the value of a student's experiment in physics requires a clear idea of the purpose of the experiment. There are (i) the simpler principle-teaching experiments, hereinafter briefly called *A*-type experiments, (ii) some intermediate experiments and (iii) the more complex *B*-type experiments, which presuppose a complete understanding of principles and emphasize instruction in the use of apparatus and measuring methods. The requirements of the *A*- and *B*-type experiments are usually contradictory, inasmuch as the former require simple apparatus and obvious methods of measurements, with little emphasis on accuracy, whereas the latter should be carried out with the best apparatus available, using, if necessary, indirect and less obvious methods of observation, for example, the method of coincidences in the pendulum experiment, to secure greater accuracy. The large number of *A*-type experiments is one of the principal features of the course in general physics at W.P.I.

In Physics 1 all experiments are of the *A* type. The equipment required is so simple that it is possible to set up 24 outfits of any one of the experiments, so that all the students in a laboratory section (there are nine laboratory sections of the freshman class) may perform the same experiment simultaneously, at a time when it fits the work taken up in lecture and recitation. The principles and details of any experiment in Physics 1 are thoroughly discussed in the preceding lecture. One example must suffice. A panel of wood of irregular shape is mounted in a vertical plane on a nail supported by a vertical board on uprights. Five forces act on the panel: its own weight, a hanging weight, the force exerted by a thread running over a pulley to a large weight, a spring and the thrust of the supporting nail. There are 15 items involved in the equilibrium equations: five forces, the five angles made by the lines of action of these forces

with a horizontal reference line and the five moment arms of the forces with respect to an axis chosen in a direction perpendicular to the vertical plane of the forces. Twelve of these items are measured directly; the remaining three are then calculated from the equilibrium equations. The three unknowns chosen are the magnitude of the force of the spring and the magnitude and direction of the force exerted by the nail. These unknowns are then checked, the spring from its calibration curve, and the force of the nail by using an auxiliary pulley, a scale-pan with weights and a thread attached to the nail. When the magnitude and direction of the latter force are correctly chosen, the nail may be pulled out from the supporting board and the panel will remain in equilibrium.

As the course proceeds, the *A*-type experiments are gradually replaced by intermediate ones and, finally, by the *B*-type. In Physics 4, for example, there are still a few *A*-type experiments on mirrors, lenses, prisms, and so forth, which are performed simultaneously by all students in a section; but the majority are of the *B* type, done in rotation and concerned with matters that the student has learned earlier. They are selected according to the department in which the student is registered. For example, a student of electrical engineering would perform, to quote a few from many, measurements on hysteresis loops, coefficients of self-induction and mutual induction, and low resistance by the double bridge, while a student of chemical engineering might measure the rotation of the plane of polarization of a sugar solution with the half-shade polarimeter, determine the heats of combustion of gaseous and liquid fuels, and so forth.

Of some 50 experiments that a student performs during the four terms of his course, nearly half are *A*-type experiments, about a dozen are of an intermediate character—volumenometer, air thermometer, Wheatstone bridge, potentiometer—and the rest are of the *B* type. Not all of the latter experiments are prescribed; the student is furnished with a list of optional experiments, among which he may choose according to his taste.

The calculations for the *A*-type experiments are performed in the laboratory and entered on a form sheet provided for the purpose, while in the case of the *B*-type a report is written outside class and handed in the following week. The reading of these reports is one of the heaviest duties of the staff.

Of the pedagogic features of the general course at W.P.I., the following might be discussed. Formerly the instruction in physics in most colleges was concentrated in a huge course, usually in the sophomore year, with a time allowance of perhaps two lectures, three or four recitations and one laboratory period per week. The writer, like many other physics teachers of the older generation, taught such a course for many years. It was never a success; the results were disappointing, the student mortality very high and the course on the whole unpopular. The chief reason was, presumably, the excessively rapid rate at which the student was confronted with new physical concepts and principles. In calculus the instructor teaches relatively few new basic concepts but many processes and operations, and a considerable part of the knowledge acquired by the student is gained through repeated trial, in the form of illustrative problems. On the other hand, in physics the teaching is not essentially of operations or processes but of ideas and concepts. In the old one-year physics course the pace was much too rapid, the ground to be covered too large and the time available for illustrative problems too short. A student, who in the early stages of, say, dynamics or electrostatics dropped behind, usually never caught up again. By spreading the course over two years, the rate of assimilation of new concepts is reduced, so that the student is more likely to digest them.

The present time allowance of the course at W.P.I. is sufficient to permit continual reviewing. Every fourth or fifth recitation is a review discussion period. Occasionally, in Physics 1 and 2, the laboratory period is devoted to a review in which the student may examine reports of preceding exercises, returned with the instructor's comments, make changes and corrections, and avail himself of the advice of the instructor on other matters. Part of these periods may be used for the consideration of selected review problems by students who have finished their report corrections. One other point might be

mentioned. Neither recitations nor laboratories are considered as grade factories. They are for the purpose of instructing the student. Grades, required by the office at W.P.I. as at practically all other colleges, are obtained chiefly from one-hour examinations in lecture periods. These come at close intervals, usually every other week. The multiple-choice type is used as well as the orthodox type. Incidentally, the experience at W.P.I. indicates that for the multiple-choice type it is an advantage to give a small number of questions with ample time allowance and expect the student to work out the answers to all of them, rather than give a large number of questions with an inadequate time allowance, expect a student to do as much as he can and invite him to guess rather than to think. These one-hour examinations are usually cumulative; they cover all the preceding work of the particular course in which they are given, not merely the work since the last examination. Thus there is constant emphasis on the idea that physics should be studied as a connected whole, not piecemeal as an aggregate of isolated facts and "formulas."

Many years ago the writer read some of the publications of Dean Seashore on sectioning by ability. The ideas set forth in these publications were put into operation at W.P.I. in 1924. The schedules for the lower two classes are so arranged that about half of each of the two classes, 80 or 90 men, have their recitations in physics and also in mathematics at the same hour. Thus these 80 or 90 men at the physics hours are completely under the control of the department of physics, irrespective of any differences of their course in other departments. Hence they may be assigned to sections by any system the department wishes to adopt.

Several different systems of divisioning have been tried. The one in use now for *second* term freshmen is as follows. Section 1 is made up of quick-thinking good students. Occasionally a bright but lazy student with low marks is assigned to this section also, in the hope that the competition with really good scholars will stir his ambition and persuade him to make better use of his mental gifts than he has so far. Of course, section 1 is likely to have the highest average grade. Section 2 consists of good students who think a bit more slowly, have to work harder, but do get results. The highest ranking men in section 2 have higher marks than the lowest in section 1. The bottom section consists of the men who have had a condition in Physics 1 or who are in danger of not passing. The teaching of this section requires considerable skill and should be entrusted to an instructor who has much patience and some sympathy with the less brilliant minds. The hopeless cases have disappeared already at this stage, for Physics 1 is a prerequisite to Physics 2. Between section 2 and the bottom section, one section, or sometimes two if the number of students is large enough to warrant it, is inserted. These sections receive all students who do not merit a special assignment to sections 1, 2, or 5. The sophomores are arranged usually in four sections, a first and second, to which students are assigned in the same manner as freshmen, and two indiscriminate sections for all others, since for sophomores there usually is no need to make up a special bottom section.

The system is quite flexible; a student can be transferred during the term, if he has been misplaced, although this is rare, because the writer knows all freshmen personally and individually and because the sections at the beginning of any new term are always made up in the presence of and with the advice of all instructors who had recitation or laboratory sections with the class in question. The sectioning of first-term freshmen in Physics 1 is a serious problem for which no adequate solution has been found. Attempts to assign sections by judging from entrance records and from aptitude tests taken by freshmen during freshmen week have not proved satisfactory. The system for the current year is to make no attempt to sift at the beginning, but to rearrange after eight weeks, in order to get all weak students into special sections with experienced instructors.

The laboratory sections, however, are not made up on any such principles. In the sophomore class laboratory sections are determined by the engineering department in which the student intends to take his degree, and in the freshman class by his section in English, language or history. Thus the recitation instructor of any student is not necessarily also the laboratory

instructor. In the laboratory, where every student works individually at his own bench, the mental homogeneity of a section, so necessary for recitation and discussion, is of no consequence. The good student merely accomplishes the same work as a weak student in less time or—what is more desirable—more work in the same time, in the form of extra suggestions for additional points, questions, challenging problems and the like.

THE PHYSICS COURSE

Students are admitted to the physics course at the end of the sophomore year, irrespective of their previous department affiliation, but only with the consent of the physics department. The requirements are: (i) the student must be a good mathematician; (ii) he must be willing to work with his fingers as well as with his head; (iii) he must be interested in physics. The first

The large lecture room.

requirement is satisfied by a student who has a grade of 90 or better in calculus. This requirement is waived, and a student is admitted with only a *B* grade in calculus if he has a good enough general record to be in the first honor group, or if he is strongly recommended by a physics instructor who is familiar with his work. This requirement is made *not* because the physics courses are taught as branches of applied mathematics but for the opposite reason. A student who does not handle the required mathematics with reasonable ease spends too much time and effort on mathematical manipulations and loses sight of the physical ideas.

Exceptional skill with tools in shopwork and in glass-blowing is, of course, desirable but hardly to be expected of young men who very rarely have had much experience in all the laboratory arts. It is important, however, that a student taking the physics course should be willing to try to acquire the necessary skill by patient perseverance. It is true that today the purely theoretical aspects of physics play a larger part in the development of the science than formerly and that work in the graduate schools is frequently very mathematical. However, an undergraduate should be trained as an experimentalist and not as a purely theoretical man.

On the average, about three or four men elect the physics course annually. As juniors they take a supplementary course in laboratory work (all experiments of the *B* type) to gain some knowledge of the experiments and methods they did not encounter as sophomores, and in addition they have some practice in laboratory arts, especially glass-blowing. In the second term they have a course in abstracts, where they read and report, orally, some papers from the literature. A certain part of this course is devoted to foreign language literature. In passing, the writer cannot suppress the remark that the ease and skill with which these men master papers in French and German, though they are students in a technical rather than an arts college, has always seemed remarkable. As seniors they work on an experimental thesis during both terms. For the rest, they take, in both the junior and senior years, certain required courses in mathematics and physics and other optional courses—in physical chemistry, electrical engineering, applied electronics, government, and so forth.

In order to avoid the necessity of giving these physics and mathematics courses every year to small numbers of men, certain courses are offered in odd years, others in even years. Depending on the year in which they begin, some students take the odd-year group as juniors and the even-year group as seniors, while the members of the next class reverse this order. One group consists of advanced calculus, thermodynamics, kinetic theory and statistical theories, optics and brief introductions to the theories of relativity and of deformable bodies. The other group comprises differential equations, mechanics, acoustics, electricity and selected topics from modern physics.

With the exception of the course in optics, these courses are largely theoretical. The omission of courses on physical chemistry and on electronics from the physics program is explained by the fact that adequate instruction in these fields is offered in the departments of chemistry and electrical engineering, respectively. These two departments make rather a specialty of these subjects, and physics students may take them as options.

Recently, further courses in optics have been added to this program. Some of these are intended as options for seniors in the engineering departments, especially chemical engineering, others are intended for men who wish to specialize in optics. These courses, which are given with the support of the optical industry, are of so recent origin, and because of the accelerated war program are given in a form so far from normal, that it would be difficult to describe them here without going into too much detail.

BUILDING AND EQUIPMENT

In the early days of the Institute the Salisbury building, named for one of the principal benefactors of W.P.I., housed all the laboratories of physics, chemistry and engineering. At present it is occupied only by the departments of chemistry, physics and chemical engineering. Several additions to it have been built recently. One contains a large room for demonstration lectures. It is used two days a week for freshman physics, two for freshman chemistry and two for sophomore physics. A center lecture table, equipped with gas, water and electric wiring, is permanently mounted in the front of the room. Exact duplicates of this table are placed both in the chemistry and in the physics preparation rooms. These preparation rooms are on the same floor as the lecture room and are accessible through wide doors. In addition to the center table each contains four tables which may be rolled into the lecture room. The physics tables are of different heights, most of them lower than is customary. These low demonstration tables have proved very satisfactory.

Of course, the room is adequately equipped with blackboards, screen, projection apparatus, ventilators and lights. It has no windows. Instead of darkening the room by closing the windows with dark shades, the operating mechanism of which easily gets out of order and in many old lecture rooms is a constant source of annoyance to everyone concerned, the lights are simply dimmed or turned off by one motion of a control switch. The operation lasts a few seconds and never fails. Possibly the ease and speed with which the room can be arranged for light or dark is one of the reasons why projection of apparatus, especially shadow projection, is being used more and more in the program of demonstrations.

For the laboratory work in general physics there are available: one large room for freshmen, with an adjoining small room for the storage of apparatus, and three laboratories for sophomores, one of them large enough to provide 42 work stations, the others providing 20 and 12 stations, respectively. Thus, on any one afternoon two sophomore sections—for example, one for students of mechanical engineering and one for electrical engineering—can be working simultaneously, and the equipment assembled for any one experiment can be left at the station for an entire term or as long as the experiment is being run. In addition to these laboratories there are a few small rooms for spectrometers, polarimeters, optical benches and similar equipment.

There are also rooms for the courses in applied optics and for seniors in the physics course doing theses. Only one room is provided for staff research; but there are three large staff offices, equipped, in addition to desk and bookshelves, with large tables, wall benches, gas, water and small switchboards, so that the occupant may engage in experimental work in his own office without fear of having his apparatus disturbed.

The collection of apparatus for teaching purposes is very extensive, both for demonstration lectures and for laboratory practice. Naturally a great deal of it is of standard make, similar to that found in other laboratories, but there is also a great deal that has been designed and constructed locally. New instructors or visitors always find a considerable amount of interesting equipment not generally known. On the other hand, special equipment for staff research is not as abundant as in some other colleges. This is due in part to lack of funds, in part to the aims of the college and its historical development.

HISTORY OF THE DEPARTMENT

The best known of the former professors of the department is, of course, A. Wilmer Duff. He was the recipient of the Oersted medal of the American Association of Physics Teachers in 1938.[1] The first of the books from Doctor Duff's pen, *Elementary Experimental Mechanics*, published by Macmillan in 1905 and long out of print, is the one in which, as far as the writer knows, the first attempt is made to aid the teaching of mechanics by a set of *A*-type experiments. Of the 38 experiments described in that book, some have been discontinued and others changed beyond recognition, but some still survive in the original form suggested in this book, tried out first by Doctor Duff's classes in his early days at W.P.I. and still effective tools of instruction now after nearly 40 years. It seems to the writer that this pioneer work in laboratory instruction is as important as some of the other achievements of Doctor Duff discussed in the biography quoted.[1]

Since this first book came out in 1905, there have been 11 books on physics brought out by various members of the staff of the department of physics at W.P.I., on the average a new book nearly every three years, surely a surprising literary activity for so small a college.

Of these books eight are written by physicists of W.P.I., two are translations, including Planck's *Heat Radiation*, the famous book in which the quantum theory first appeared, and one is the posthumous *Partial Differential Equations of Mathematical Physics*, by the late A. G. Webster, edited by S. J. Plimpton of W.P.I. Of these books, one had eight editions, three had three editions and one, two editions. Including reprints with corrections, which were not counted as new editions by the publishers, there has been one book run through the press, on the average, practically every year.

The achievements in physical research at W.P.I. fall somewhat short of those in teaching and literary work. There are reasons for this, but there also has been some bad luck. Duff and Olshausen had virtually completed an experimental investigation on the magnetic fields of cathode rays, when the paper of Joffé appeared. A few years later, the writer suffered a similar fate—anticipation of his results by another investigator, in pursuing some ideas arising from the functional relation of entropy and probability.

Since then no member of the staff has attempted any research in the vanguard of modern physics. The rate of progress of an investigator in a small college, who is devoting nearly all his time to teaching and is dependent to a large extent on the amount he can accomplish during the summer, is so much slower than that of a research professor, research associate or other individual who is devoting his time almost completely to research, that he is certain to be outdistanced in the race. It is highly desirable that a college teacher of physics be a productive scholar as well as a teacher, but it is not necessary that his investigations be in the most modern fields, on the firing line so to speak. Accordingly, the papers that have come from the laboratory of W.P.I., on the average between one and two per year, are, with few exceptions, in some field that at the time of publication was not in the foreground of interest. It is not possible to enumerate all the topics, scattered over the entire domain of physics; however, two papers may be mentioned, not perhaps the most important, but typical illustrations of these explorations of the bypaths of physics.

If a cylinder of transparent jelly is twisted about its axis, the plane of polarization of light is rotated in the passage of the light through the cylinder. An exhaustive study of this curious phenomenon was made at W.P.I.[2]

The exponent 2 in the inverse-square law of action between electric charges was first established experimentally by Coulomb. By pursuing an indirect method attributed to Cavendish, but not the Cavendish method customarily discussed in the introductory textbooks of physics, Maxwell[3] was able to show that the exponent differs from 2 by less than 1 part in 26,400. An investigation at W.P.I.[4] has reduced

[1] For an account of this award and a brief biography, see Am. J. Phys. (Am. Phys. T.) 7, 49 (1939).

[2] A. W. Ewell, "Artificial rotatory polarization," Phys. Rev. **33**, 480 (1911).

[3] Maxwell, *Electricity and magnetism*, Vol. I, p. 83.

[4] S. J. Plimpton and W. E. Lawton, "A very accurate test of Coulomb's law of force between charges," Phys. Rev. **50**, 1066 (1936).

A corner of the large sophomore laboratory.

the possible difference of the exponent from the value of 2 to 1 part in 10^9.

The earlier history of W.P.I., from its founding as the Worcester County Free Institute of Industrial Science in 1865 to about 1900, is undoubtedly of some interest locally and to the alumni of W.P.I., while the methods of shop practice and instruction of students in the department of mechanical engineering form an interesting chapter in the history of engineering education in the United States; but there is no record of any outstanding contribution either in research or in teaching made by the physics department during that initial period. At the very first, the physics department seems to have conducted, under the name *practice*, all laboratory work except that done in the shops and in chemistry. Gradually, with the growth of the Institute, engineering laboratories were established, and in 1896 electrical engineering became established as a separate department. Dr. Alonzo S. Kimball, who was Head of the Physics Department from 1872 to 1898, was a competent physicist and a successful teacher, even though his work did not become well known outside of Worcester. His chief interest apparently was in acoustics. There still is at W.P.I. a magnificent collection of tuning forks from König in Paris.

During the interregnum between Doctor Kimball and Doctor Duff, the physics teaching was supervised by T. C. Mendenhall, then president of W.P.I. One curious feature of this period was related to the writer some time ago. It seems that President Mendenhall was a great believer in quantitative measurements of the *B* type. If a student measured the magnetic field of the earth by Gauss' method and the dip circle, his results had to be good, and he was not allowed to go on to another experiment until they were. Some students had to repeat again and again. It is debatable whether a laboratory course of the *B* type should aim at covering much ground, many instruments and methods, or only a limited set of exercises, each done to perfection, or a compromise—the latter is the policy of the department at present—but it is certain that President Mendenhall's method made the course very unpopular among students.

Not all the physicists connected with W.P.I. have remained for so long a time as Doctor Kimball, 26 years, Doctor Duff, 37 years, Doctor Ewell, 39 years and the writer, 33 years, with the hope of a few more; and perhaps a few names should be mentioned of men who, after leaving W.P.I., achieved some success as writers, for example, R. J. Stephenson, of the University of Chicago, or M. F. Manning, of the University of Pittsburgh, or by performing a noteworthy experiment, as did R. A. Bethe at Princeton University. The most famous of these is the writer's friend and former roommate, A. W. Hull.

According to the best New England traditions, W.P.I. has recently opened its doors to receive refugee scholars. The most prominent of these, to whom W.P.I. was a haven of refuge for four years, is K. W. Meissner, whose recent report on interference spectroscopy[5] was written at W.P.I.

This brief sketch of the activities of the physics department at W.P.I. presents the normal peacetime arrangements. No attempt has been made to include a discussion of the changes created by the wartime emergency schedules.

[5] J. Opt. Soc. Am. **31**, 405 (1941).

Take advantage of all the little opportunities that come along, and you won't worry much about the occasional big ones that got away.—THE KALENDS of the Waverly Press.

Physics and Mathematics in the War Training Program at Brown University

R. B. Lindsay
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THE war in which we are engaged has served to bring out in sharper outline some of life's little ironies. Only a few years ago, teachers of physics in secondary schools and a few of those college teachers who snatch a moment now and then to reflect on the source of the wherewithal to keep the wolf from the door were wondering what could be done to save secondary-school physics from the fate of Latin and Greek—ultimate extinction from the curriculum. Only a few years ago some of us were worried over the empty seats in our intermediate and advanced college physics classes. Even the elementary classes often seemed too full of those who were compelled to take physics for professional reasons and too empty of those who really felt it to be a subject interesting for its own sake. Students were in the habit of asking: what good is physics anyway except for pre-engineers and premedical students? We no longer have to rack our brains over the answer. Hitler has answered the question for us! And now the problem is to find seats enough in our lecture and recitation rooms for those who have awakened to the fact that this is a physicist's war.

It is not my intention to dwell on the troubles of a physics department in a small university with a strong professional chemistry department and a strong engineering division acting continually to siphon off promising candidates who might otherwise concentrate in physics—a physics department which, save for an ambitious graduate program, was largely in the "handmaiden" class. When the war brought about a rather sudden transition from the Cinderella to the fairy princess category, it was rather flattering to our pride but also brought us face to face with some serious problems, which of course are by no means peculiar to our institution. Immediately after the declaration of war Brown University set up a division of war training courses, and it was at once discovered that of the total of 19 courses deemed necessary, five would have to be taught in the physics department, namely, acoustics, physical meteorology, photography, radio and ultra-high frequency technics. This was the largest number of courses assigned to any single department. Contrary to some preliminary expectations the students elected these courses in considerable numbers and what with the laboratory problem the initial semester was a veritable merry-go-round, with the fun made just a little more fast and furious by the fact that we had on our hands the largest group of finishing Ph.D.'s ever to receive their degrees at one time at Brown.

There is no necessity for discussing in detail the special war training courses in physics. These doubtless have followed the pattern set in most other institutions and there has been little of original character to mark them. I shall therefore confine my remarks to two specific parts of our program that may be of greater general interest. The first of these is not indeed directly connected with the physics department, though its ultimate influence on the relations between physics and mathematics may be profound. I refer to the program of Advanced Instruction and Research in Mechanics, the word "mechanics" here being a scarcely disguised euphemism for *applied mathematics* or, more specifically, *mathematical physics*. The second item is the program in the physics department for advanced training in acoustics.

Before describing these two programs, I should mention that we feel we have materially strengthened our ability to serve the war effort and the postwar needs by introducing a course of study leading to the degree of Sc.B. in Physics. To a certain extent this parallels the already well-established professional course in chemistry, but it is a more flexible arrangement which allows the student to combine his study of physics with a strong optional minor in either chemistry or engineering and at the same time to obtain a thorough mathematical background through advanced calculus.

To come back to the applied mathematics program, I must confess at the outset that I am hardly the proper person to do justice to the

topic. This demands the gentleman whose uncanny intuition, persuasive tongue and tireless energy have made the program possible. It is a monument to the vision and persistence of Dean R. G. D. Richardson of the Brown Graduate School. The program began in the summer of 1941 with six lecture and seminar courses in partial differential equations of physics, hydrodynamics and elasticity. There were also numerous special lectures by visiting experts on a wide variety of topics in applied mathematics and mathematical physics. Some 64 students took advantage of the 12 weeks' summer session. The program was continued on a somewhat smaller scale during the academic year 1941–42. The summer session of 1942 has been on a more elaborate basis with over 100 students attending 13 courses covering, in addition to the topics previously mentioned, material in aerodynamics, plasticity and electromagnetic wave theory. Opportunity has been provided also for properly qualified students to undertake research in the fields treated in the lectures. The program is continuing through the balance of the academic year 1942–43 with renewed emphasis on the research program and with the award of substantial fellowships to qualified students.

Details are likely to be boring and so I shall go on to give my own impressions of the need for and value of such a program. In brief, the object seems to be twofold, namely, to sell mathematics to the engineers and to help the pure mathematicians realize that there *is* an external world for the description of which mathematics is an ideally suited language—perhaps the most remarkable language ever invented by man. As a physicist I am inclined to consider both aspects as laudable; at the same time I fear the task involved is pretty tough. From my observation I should say that most engineers are likely to be sceptical of the practical value of mathematics, at any rate in its advanced stages. On the other side it is common knowledge that the pure mathematician, insofar as he *is* pure, does not live in this world and has no use for it. Pure mathematics is indeed a fearful and wonderful thing—that game in which, as the eminent author of *Marriage and Morals* so well said, "we never know what we are talking about nor whether what we are saying is true." It is a game in which the ultimate object appears to be to say as much as possible with a minimum use of language—only the pure mathematician has been able to compress so much into so little space. But it is economy for economy's sake. It is foolish to ask of what use it all is: one might as well ask of what use is a work of art!

Now it is a fact that a large part of mathematics was developed as a more satisfactory language for the description of natural phenomena than the language of ordinary daily life. As physical discoveries accumulate, the need for new mathematical methods becomes more pressing. Of course it is possible to take the stand that in the last analysis all practical applications of mathematics to physical description can be reduced to ordinary arithmetic. The hard-boiled engineer is ever ready to remind us that all integrations can be carried out with sufficient accuracy by mere counting or, better still, by developing machines to do the counting for us. All differential equations—as long as we stay away from singularities—can be solved by purely numerical methods which have now been pretty completely standardized and reduce essentially to glorified arithmetic. What then is the advantage to be gained in the use of more esoteric devices save to flatter someone's vanity and sense of self-importance?

The question overlooks one of the commonest of human urges, namely, the tendency to look for short cuts in the solution of all problems. Any one who can make a few passes over a given set of data and arrive at a theoretical prediction amply verified by experiment has actually saved money, and that is an argument which impresses even engineers. For example, we find the engineers ultimately seeing merit in a mode of analysis such as the Heaviside operational calculus. Another advantage of new mathematical technics is that they often lead to quite new predictions and hence open up new fields of development. Think in this connection of the importance for engineering of the exploitation of electromechanical analogies! These are fundamentally mathematical in nature, based on the fact that the differential equation for charge as a function of time in an oscillating circuit is of the same form as the equation of motion of an oscillating dynamical system. Thus the mathe-

matical study of the vibrations of a string loaded at equal intervals with heavy masses led directly to the concept of the electric filter. Similarly, the mathematical analysis of electric filters suggested the invention of acoustic filters. It is difficult to see how these results could have ensued from mere physical intuition based on observation alone. Or does anyone think that a cylindrical tube with alternate constrictions and expansions *looks like* an iterated combination of coils and condensers? It is only when we examine the two structures mathematically that we see the fundamental similarity and recognize that both are energy-transmitting systems which are selective with respect to frequency.

Applied mathematics and, in particular, mathematical physics forms a vast discipline and a difficult one. In fact, as a human occupation it is usually more difficult than pure mathematics. The reason is simple: the pure mathematician is entitled to make up his own problems and, upon encountering one that is too tough, can always set it aside and look for another, or at any rate introduce some modification to render the thing more tractable. On the other hand, the applied mathematician has his problems given to him by Nature—he must not wholly evade them nor try to substitute other quite different ones of his own making for those which appear too difficult; he is bound to produce some sort of solution which the physicist or engineer can use. Clearly the applied mathematician not only needs an extraordinarily good mathematical training but must also be conversant with the practical problems which are crying for solution. It is just here that the Brown University program can make a worth-while contribution by directing the attention of the competent pure mathematicians to the possibilities of applied mathematics. If I stress this side of the project more than the mathematical education of engineers and engineering students it is not because I believe it is hopelessly impossible to ram mathematics down the engineers' throats, but because I think it will be easier to convince them of the value of mathematics when they get further evidence of its power in meeting very practical situations with a maximum of economy. Of course the abler engineering students ought to have more elaborate training along mathematical lines. Possibly it is also not out of place to stress the value of more fundamental physics than most of them get!

It is to be hoped that one of the results of programs such as that at Brown will be to lead the strong mathematics departments of the country to give greater encouragement to the presence of applied mathematicians on their staffs. It is fine to have people around who can prove logically that a solution to a problem *exists*, but it is even better to have a few who can really *find* the solution in the shortest and simplest way and are willing to teach others how the trick is done.

In turning now to a brief description of the ESMWT acoustics center at Brown during the summer of 1942, I shall venture a few opinions about the general position of acoustics in our institutions of higher learning.

For many years in our colleges and universities acoustics has been a stepchild of physics. I can remember vividly how, as a young instructor at Yale and like most young instructors bitten with the bug of desire to try my hand at an "advanced" course, I approached the higher-ups in the department with the request that something of the sort be allotted to me. The decision was to let me offer a course in sound. It was pointed out that nobody else would ever want to do it anyway! I suspect that my experience has not been unique. Not so long ago most university physicists felt that the theory of sound stopped with Rayleigh in 1877—one might almost say *died* with the publication of his celebrated book. In truth the subject underwent rejuvenation during the first World War, and several distinguished university teachers collaborated on research in military acoustics. After the war, however, with a few conspicuous exceptions, intensive work in acoustics was abandoned by university physics departments, and the rapid and almost revolutionary expansion of the field, particularly in electroacoustics, was left to industrial and governmental laboratories. It is in these latter places that the greatest progress in acoustics during the last 20 years has been made. The formation of the Acoustical Society of America in 1928 gave a tremendous stimulus to acoustical research, but here again with a few exceptions

it is the non-university laboratories that have shown the greatest interest. A glance at the list of members and the recent officers of the Society will confirm this statement. It is, of course, gratifying that the industrial and non-academic development of acoustics has been so great, but it is nonetheless depressing to find such a fascinating science so neglected by our atom-smashing colleagues. It is sad for more reasons than one, but not least for its bearing on the present emergency. The urgent need for well-trained workers in acoustics has proved impossible to meet. This is particularly true among the younger men who are the ones most sought after because of the rather strenuous character of field work. The ESMWT program in acoustics owes its existence to a recognition of this situation and has as its aim the production of a reservoir of trained personnel for work in government laboratories.

The summer course at Brown was given for a period of 11 weeks to a group of about 25 students, including seven recently appointed to positions at the U. S. Army Signal Corps Development Laboratory and sent to take the work before entering upon regular employment there. The lectures stressed basic principles of sound on the advanced level, including particular reference to electroacoustics, supersonics and elastic wave filtration, fields in which we have been interested from the research point of view at Brown University for a number of years. The laboratory work involved the performance of ten substantial experiments, including oscillator and microphone calibration, measurement of acoustic impedance, transmission through acoustic filters, reverberation time and normal modes of a reverberant chamber, construction of voltage amplifiers, measurement of supersonic absorption in water, and so forth. In each case stress was laid on the behavior of the electric equipment which has now become the *sine qua non* of acoustical research.

It is interesting to speculate whether the present training program will encourage greater academic interest in acoustics after the war. Acoustics has great attractiveness both on its experimental and theoretical sides. Some of its unsolved problems are difficult enough to challenge the utmost mathematical ingenuity. The field of supersonics, in particular, borders closely on the domain of quantum theory. There are fascinating relations with chemistry, biology, medicine, psychology and engineering well worth the close attention of the academic investigator. In an age of specialization acoustics provides an unusual opportunity for the physicist who is striving to realize a little more nearly the ultimate aim of science, namely, the achievement of *unity* in all branches of scientific investigation. It will be most gratifying if its well-recognized value in war shall bring it greater academic recognition in the peace to which we are all looking forward.

Radio in Negro Colleges and Universities

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RADIO communication is today one of the essential fields in which the demand for trained men and women far exceeds the supply. The present article purposes to show how the Negro colleges and universities are endeavoring to meet the need. Training in radio, begun about 15 years ago in one Negro college, is now offered in more than 20 Negro colleges and universities throughout the country.

The information contained in this survey was obtained from questionnaires sent to the presidents of 56 Negro colleges and universities having a four-year program leading to a degree. No distinction was made between liberal arts colleges and technical schools since radio can be taught by any science department that has qualified instructors. Replies were received from 44 of these institutions. Information obtained from catalogs shows that at least three of the remaining 12 colleges offer courses in radio, apart from the usual discussion found in physics courses, but no further reference will be made to

colleges not reporting. The 56 colleges and universities surveyed do not include all the Negro institutions of college grade, nor does the survey explore the vocational and trade institutions. Some information on activities in the radio field in trade schools is available, but this work is more vocational in nature than that offered in colleges.

Since an adequate survey of physics departments in 45 Negro colleges has already been made,[1] no reference is made to physics curriculums, faculties and ratings of these colleges and universities.

The institutions that replied to the questionnaires and the states in which they are located are as follows:

Alabama: Talladega College; Tuskegee Institute
Arkansas: Agricultural Mechanical and Normal College
District of Columbia: Howard University
Florida: Florida Agricultural and Mechanical College; Florida Normal and Industrial College
Georgia: Georgia State College; Atlanta University; Morehouse College; Clark College; Fort Valley State College; Paine College
Kentucky: Kentucky State College; Louisville Municipal College
Louisiana: Xavier University; Dillard University
Mississippi: Alcorn Agricultural and Mechanical College
Missouri: Lincoln University
North Carolina: North Carolina College for Negroes; Fayetteville State Teachers College; Bennett College; St. Augustine College; Shaw University; Livingstone College; Winston-Salem Teachers College; Agricultural and Technical College; Elizabeth City State Teachers College
Pennsylvania: Lincoln University
South Carolina: Benedict College; State Agricultural and Mechanical College
Tennessee: Le Moyne College; Fisk University; Lane College
Texas: Texas College; Wiley College; Prairie View State Normal and Industrial College; Bishop College; Samuel Houston College; Tillotson College; Mary Allen College
Virginia: Virginia State College for Negroes, Hampton Institute
West Virginia: Storer College; West Virginia State College

The type of training given varies from elementary courses to advanced radio and radio mechanics. Of these courses, 52.2 percent are financed by the colleges and the remaining 47.8 percent by the Vocational Training, NYA, EDT or ESMDT programs of the U. S. Office of Education. Table I lists the colleges and universities that offer courses in radio and the type of course offered. Nine colleges and universities that include radio as a part of the one-year general physics course are not listed in the table. All the institutions listed also give radio as a part of the regular one-year general physics program in addition to the courses listed. This table also gives the numbers of students, male and female, enrolled in the various radio courses during the academic year 1941–42. The credit for each course is given in semester hours (s.h.) or quarter hours (q.h.). The short courses marked with the asterisk vary from 30 to 180 contact hours. It will be seen that 589 Negro men and women were trained in some phase of radio in the academic year 1941–42.

In the 15 years during which radio in some form has been taught as a full-time course, 569 Negroes with some training in the field have graduated. Of these 29 are licensed operators and 52 have been placed in radio laboratories, in radio manufacturing plants or as instructors in radio at various types of institutions. It is not known how many of the 569 are now in the armed forces working in the radio field or are employed as commercial radio service men.

The value of the equipment of the institutions listed in Table I that is used exclusively for radio varies from $100 to $12,000. There are 23 part-time and 13 full-time radio instructors in the 21 colleges and universities offering one or more courses. Eleven of the 21 are liberal arts colleges offering no technical training.

Twenty-three of the 44 colleges reporting, or 52.3 percent, do not have a full-time course in radio; of these, 13 plan to start full-time classes in radio in the near future, while the remaining 10 indicated that they were not interested in this field. The chief reason given for this attitude was the lack of necessary equipment. Plant facilities are available in the event that the Government or any other institution now offering radio should desire to establish a class and furnish the equipment at these colleges.

The survey discloses that a large percentage of the Negro colleges and universities have made tremendous advancement in this field on their own resources; and that recently, because of

[1] Woodson, "The present status of physics in Negro colleges," Am. J. Phys. 9, 180 (1941).

TABLE I. Names of radio courses and institutions offering them.

Institution	Course	Credit	Total Students Male	Total Students Female
A. M. and N. College, Arkansas	*Radio servicing		8	2
Atlanta University	Fundamentals of radio	3 s.h.	6	
Morehouse College	Fundamentals of radio	3 s.h.	34	6
Fayetteville State Teachers College	*Radio code			
	*Amateur radio theory		15	30
Fisk University	*Radio technology		16	4
Florida A. and M. College	*Fundamental d.c. and a.c. theory			
	*Fundamental radio theory		6	10
	*Radio frequency problems			
	Amateur radio communication	3 s.h.		
	*Advanced servicing problems			
Hampton Institute	[1]Elementary radio			
	[2]Advanced radio			
	[3]Radio drafting			
	*Radio repairing (basic)			
	*Radio repairing (adv.)			
	*Radio operating science		20	10
Howard University	Electronics	3–11 s.h.		
	*Radio technology A		30	
	*Radio technology B		30	
Lincoln University, Missouri	Principles of radio communication	3 s.h.	9	
	Laboratory in radio communication	2 s.h.	9	
Louisville Municipal College	Radio principles and repair I	3 s.h.	4	1
	Radio principles and repair II	3 s.h.	3	
	*Fundamentals of radio		37	
A. and T. College, North Carolina	Communication	15 q.h.	10	2
	Radio circuits	5 q.h.	5	
	*Radio communication		20	
	Radio servicing	10 q.h.	10	
North Carolina College for Negroes	Radio theory	5 q.h.		
	†Radio communication		20	
Prairie View State College	*Radio engineering			
	*Fundamentals of radio communication		12	3
	Radio communication	3 s.h.	7	18
State A. and M. College, South Carolina	*Radio repair		15	
St. Augustine College	†Radio communication		10	
Shaw University	†Radio communication		7	3
Talladega College	Fundamentals of radio		1	1
Tillotson College	Radio fundamentals	3 s.h.	7	1
Tuskegee Institute	Basic radio circuits	2 q.h.	5	
	Radio servicing I	2 q.h.	10	
	Radio servicing II	2 q.h.	10	
	Radio circuits (adv.)	3 q.h.	10	
	*Radio communication		10	
Virginia State College for Negroes	Fundamentals of radio	3 s.h.	34	
	*Radio communication		19	
	Radio mechanics	3 s.h.		
West Virginia State College	*Mechanics learner—radio		41	5
	*Junior repairmen—radio		3	
	Total		493	96

* Short courses financed under the ESMDT, EDT, Vocational Training or the NYA program varying from 30 to 180 contact hours.
† Short courses of 180 contact hours offered in cooperation with another institution under the ESMDT program.
[1] 5½ hr/wk. [2] 3½ hr/wk, first semester; 17 hr/wk, second semester. [3] 1 hr/wk, first semester; 2½ hr/wk, second semester.

financial assistance through various federal and state agencies, additional institutions have been able to offer or will soon begin courses in this field. With expanding opportunities for employment in war industries and opportunities in the Army, the Navy, aviation, civilian defense and radio manufacturing plants, the outlook for the Negro youth of today in this field is very hopeful.

Modern science, when devoted wholeheartedly to the general welfare, has in it potentialities of which we do not yet dream.—HENRY A. WALLACE.

The Physics of Automobile Driving

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ONE of the most important factors affecting the driving of an automobile is the frictional force between tires and road surfaces under various road conditions. Thus, one may well begin a classroom discussion of automobile driving by referring to experimental measurements of the maximum forces of friction for rubber sliding on surfaces similar to those found on roads under certain weather conditions.

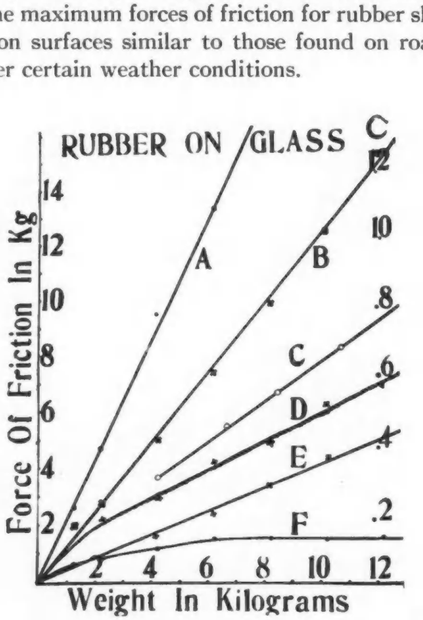

Fig. 1. Frictional force for rubber sliding on glass. *A* and *F*, smooth tires; *B*, *C*, *D* and *E*, treaded tires. *A* and *B*, clean rubber on clean glass; *C*, dry rubber on dry glass; *D* and *F*, wet rubber on wet glass; *E*, oily rubber on wet glass.

Figure 1 illustrates results that have been found in the laboratory for miniature tires sliding on glass plates. Although a concrete floor gave practically the same results under similar conditions, it is much more convenient to alter the surface conditions of the glass plate than those of the floor, and the former is much easier to clean. This also makes a good demonstration experiment on friction. It shows that the coefficient of friction $C[=F/W]$ is constant for different loads and small speeds. Values of C are given in the right-hand column in Fig. 1.

The most striking observations were made when extremely clean tires and equally clean glass were used. The smooth tires (curve *A*, Fig. 1) developed much more friction than the treaded ones (curve *B*). In both cases the force required to drag the loads was larger than that needed to lift them; that is, in both cases, the coefficient of friction exceeded unity. These experiments not only show that it is possible for C to exceed unity without one of the surfaces being torn up but also afford a possible explanation of some known instances in which sharp turns were made successfully at a speed previously considered impossible. For dry surfaces the frictional force appears to be proportional to the area of rubber in contact with the road. This is not true for wet or muddy surfaces, on which smooth tires have very little traction (curve *F*).

Curve C was obtained with a small treaded tire, apparently clean, inflated to a pressure of about 25 lb/in.^{2} and dragged along a clean, dry glass plate. The coefficient of friction for this tire was 0.8, which is quite near the value 0.79 found by the New Jersey State Police some years ago in road tests for speeds up to 40 mi/hr. At 60 mi/hr on dry pavements the New Jersey tests indicated a coefficient of only 0.70. This reduction resulted largely from the softening of the rubber by the heat which developed after the tire was dragged along the surface for some distance. However, R. A. Moyer[1] has shown that the coefficient of friction for wet pavements also decreases somewhat with increased speeds.

The importance of the tread on tires is shown by curves *D* and *F*. For a wet tire on fairly clean wet glass, the treaded tire shows only a small decrease in traction, whereas a smooth tire on the same wet track shows very little traction and, once started sliding, undergoes little change in speed unless new rubber is laid down by allowing the wheel to turn. Thus, there is some reason for the rule that a driver should apply brakes inter-

[1] Moyer, "Skidding characteristics of automobile tires on roadway surfaces and their relation to highway safety," Iowa Eng. Exp. Station Bull. 120 (1934).

mittently and stay in gear on slippery roads. If the car begins to skid, the braking should be reduced until the tires take hold again; then more braking can be applied.

The coefficient of friction may even be less than 0.1 when roads are very muddy or wet and icy. Snow and ice, if much colder than 32°F, act like most other solids and afford considerable traction; but at temperatures near 32°F they melt under pressure, and a loaded tire will be separated from the surface by a layer of water and so develop little traction.

The equations and their combinations most useful for the purposes of the present discussion are

$$s_0=vt_0,\quad F=Ma,\quad W=Mg,\quad C=F/W=a/g,$$
$$Fs=\tfrac{1}{2}Mv^2=\tfrac{1}{2}Wv^2/g,\quad a=v^2/R,$$

$$s=s_0+s_1=vt_0+\tfrac{1}{2}v^2/gC, \tag{1}$$

$$R=v^2/a=v^2/Cg=2s_1. \tag{2}$$

Here t_0 is the reaction time, or the time to set the brakes $[=\frac{3}{4}\text{ sec}]$, s_0 is the distance traveled in the time t_0, s_1 is the distance traveled after the brakes are applied, v is the initial speed, F is the frictional force, M is the mass of the automobile, W is its weight, a is the acceleration, C is the coefficient of friction and R is the radius of curvature.

Figure 2 shows the distances required to stop an automobile that is traveling with various speeds. These values were computed from Eq. (1) by making t_0 equal to $\frac{3}{4}$ sec—the value found by the New Jersey State Police to be the average reaction time required by drivers to set their brakes after they see the need for doing so. The values used for the coefficient C are those found in the laboratory for low speeds. They are evidently too large for the higher speeds, and the distances are correspondingly too small. In most cases the variations are not large, except for certain wet roads. It is worth noting that an automobile going 60 mi/hr will move 66 ft before the average driver can set his brakes, and if C remains at 0.8, it will go 150 ft farther, or a total of 216 ft, before it stops. If C is 0.7, the total distance traversed for 60 mi/hr would be 237 ft, but for 30 mi/hr would be only 71 ft. Usually C is less than 0.8, and the stopping distances are greater. For muddy roads or mud on a pavement C may be less than 0.3, in which case the stopping distance for a speed of 30 mi/hr will be more than 133 ft. On icy roads, where $C=0.1$ or less, the stopping distance for 30 mi/hr exceeds 334 ft. Although no driver would be foolish enough to expect to stay on such a road at speeds greater than this, the predicted stopping distances for such excessive speeds are shown at the bottom of Fig. 2.

Some drivers cannot seem to realize the enormous forces a road must exert upon an automobile to cause it to execute a sharp turn. The centripetal force necessary to keep an automobile moving with a speed v in a circle of radius R varies as v^2/R. The mass M of the car does not affect the maximum speed for a given radius R and coefficient C. The force of friction is larger for a heavier car, but the centripetal force is correspondingly larger. The heavier car with larger tires and springs may hold a straight road better than a lighter car; but, owing to slippage of the rear wheels, it may not be able to make a turn at as high a speed.

As shown in Figs. 3 to 7, the greatest speed possible on a curve depends upon the coefficient of friction and the radius of curvature. In Fig. 4 the curved lines represent the tracks of the four wheels of an automobile making a right-angle turn on streets 40 ft wide. The inner track is that of the inner rear tire, which "cuts in" about 1 ft closer to the curb than the inner front tire when R is 48 ft—the greatest possible radius for a right turn without getting over on the wrong side of either of the 40-ft streets. Many drivers fail to allow enough room for this "cutting in" of the rear wheels and thus injure their tires on curbs or "sideswipe" other cars. A driver making a right-angle turn on intersecting roads 15 ft wide

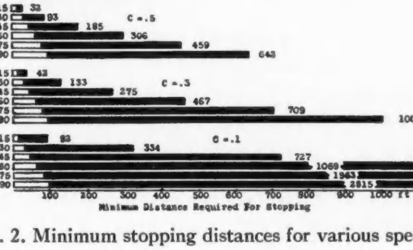

FIG. 2. Minimum stopping distances for various speeds.

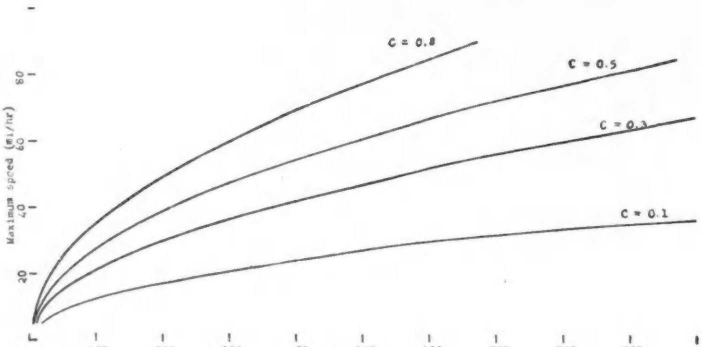

FIG. 3. Speeds on curves.

must allow more than 2.6 ft for this cutting in of the rear wheels and, in doing so, must use nearly all of the 15 ft of each road in making the turn. This corresponds to a turn with a radius of 15 ft. The maximum speeds possible in making such a turn are 13, 10, 8 and 4 mi/hr when the coefficients of friction are 0.8, 0.5, 0.3 and 0.1, respectively.

A simple way of judging the radius of curvature available for a right turn is shown in Fig. 4. It is evident from the figure that the maximum radius of curvature, 48 ft, is approximately the distance of the driver from the corner at the time when he begins to make a symmetrical right turn around the corner, while keeping on his own side of the street. The maximum speeds around this curve are shown on the chart for the different kinds of road surface, calculated for values of C varying from 0.8 to 0.1. Owing to the variation in load on the front and rear wheels and other factors, it is not safe to count on as high a value of C as is possible for stopping in a straight line.

In Fig. 5, the track of the left rear wheel is the only one shown for each of three cases. Track *2* indicates that it is possible to make a left turn on 30-ft streets on a curve with a 46-ft radius without encroaching appreciably on the left side of either street. Cutting the corner as close as possible (track *1*) would allow a radius of 82 ft, and the possible speeds on this curve are shown to vary from 31 to 11 mi/hr. If another car should appear at the intersection after the driver had started to round this corner at 31 mi/hr, he could not avoid an accident because he would move 34 ft before he could set his brakes and change his course and, after his brakes were set, would slide an additional 31 ft while his speed was being reduced from 31 to 15 mi/hr, the maximum speed possible to make the turn on track *3*. This total distance of 65 ft is much greater than the 50 ft from the beginning of track *1* to that of track *3*. If we calculate the time saved by cutting the corner on track *1* at the maximum speed, compared with the time necessary to slow down to the speed of 26 mi/hr for track *2* and to accelerate again to 31 mi/hr after completing it, we find the difference to be only 0.7 sec. This saving seems hardly worth the risk taken.

In these calculations no allowance has been made for the gyroscopic action of the wheels when they are being turned about a vertical axis. In making a turn the reaction is such that the outer wheels bear down on the road with more than normal force while the inner wheels bear down with less force, so the total frictional force between the tires and the road is affected very little by the gyroscopic action of the wheels. During a left turn the gyroscopic action of the

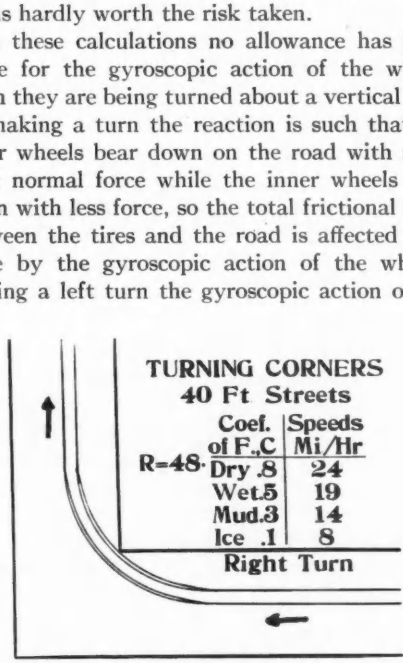

FIG. 4. Right turn at intersection of 40-ft streets.

flywheel of the engine, which spins about an axis parallel to the length of the car, is such as to cause both front wheels to bear down with more than normal force and the rear wheels to be raised and have less traction. For a right turn the opposite reactions occur. Both of these effects are very small, much less than the effects shown by Figs. 6 and 7, where a right turn is on the inside of the curve, with a radius 10 or 15 ft shorter than that for a left turn on the outside of that curve. However, a small skid on a left turn will put a wheel off in the rough, whereas a similar skid on a right turn merely gets a wheel over on the wrong side of the middle line. The rear wheels are much more likely to skid on a turn and are more easily pulled out of the skid by reducing the force on the brake or the accelerator pedal. Some racing drivers often plan rear-wheel skids in order to make a turn as quickly as possible. In making a turn a driver should remember that both the centrifugal force and the gyroscopic actions of the wheels tend to make the car tip over. Thus it is dangerous to speed on curves that are not banked. This is especially true for left turns on roads with much crown and no banking.

On curved roads it is much better to slow down while approaching a turn and then to accelerate on the sharpest part of the curve. The accelerating force has a component directed toward the center of the curve which opposes the centrifugal action, thus making the resultant force more nearly parallel to the length of the car. When this method is used the passengers hardly know they are making a turn. On the other hand, application of the brakes while making the turn develops a force in the opposite direction, tending to

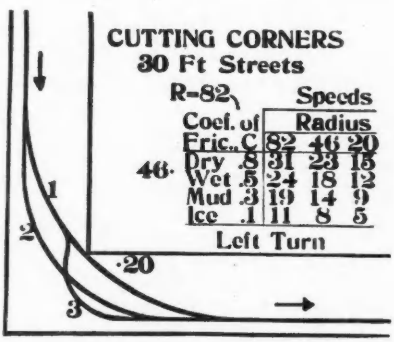

FIG. 5. Left turn at intersection of 30-ft streets.

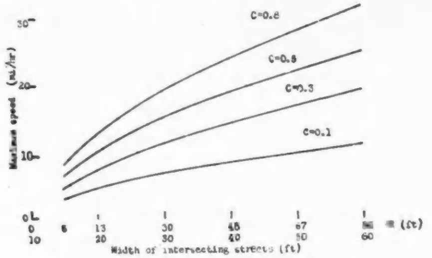

FIG. 6. Maximum speeds for left turns.

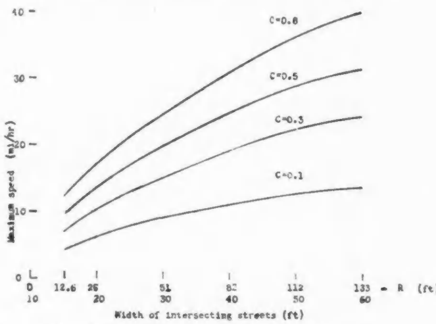

FIG. 7. Maximum speeds for right turns.

straighten out the front wheels, making the car hard to steer and throwing the occupants forward and outward.

As shown in Figs. 4 and 5, the radius for a left turn on 30-ft streets is 46 ft, almost as large as the 48-ft radius for a right turn on the 40-ft streets. Maximum speeds for left turns are much greater for all street widths and coefficients of friction, because the radius of curvature R can be larger; for instance, 133 ft compared with 86 ft for a right turn on 60-ft streets. Figures 6 and 7 show the speeds possible on curves of various radii and for different coefficients of friction.

Most accidents occur on straight highways, probably because many people cannot judge distances or speeds accurately. Taking 66 ft as the free distance necessary for one car to go around another, it is evident that an automobile moving 30 mi/hr (44 ft/sec) can go around a parked car in 1.5 sec. However, if the car ahead is moving 15 mi/hr, the relative speed is only 22 ft/sec, and the time necessary for passing is 3 sec. The total distance traveled in that time is 132 ft. If, during this time, a third car were approaching at 60 mi/hr (88 ft/sec), it would have to come a distance of 264 ft, and the clear distance between

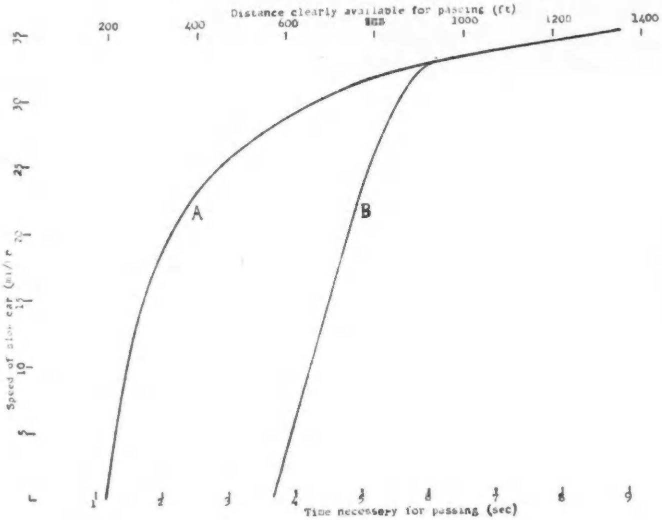

FIG. 8. Time and distance needed to pass a car of given speed when the passing car: *A*, has a constant speed of 40 mi/hr; *B*, slows down to the speed of the slower car before passing it.

the driver and the approaching car when the former began to pass should be $132+264=396$ ft. This is the space required when the driver does not have to reduce his speed as he comes up behind the slow car. However, if traffic demands that he slow down to the speed of the car ahead and then accelerate as much as possible with a powerful engine, he will need at least 5.5 sec to get around the slow car. During this time he will have traveled 187 ft, and the fast approaching car will have come 484 ft. Hence, he must have seen a clear space of at least 671 ft before starting to pass the slow car. These calculations are based on a car capable of increasing its speed from 6 to 30 mi/hr in 8 sec. A less powerful car would require still greater free space for passing. The most effective plan for passing a slow car when traffic is heavy is to remain at least 60 ft behind it until favorable conditions seem to be approaching, then begin to accelerate at a time such that one's car will have closed the gap and be moving at least 15 mi/hr faster than the car ahead at the instant the last approaching car has gone by. The time required to pass will then be less than 3 sec. If the relative speeds differ by 30 mi/hr, the time for passing is only 1.5 sec and the free space needed is much less. If there is a hill or a turn that prevents the driver from seeing the necessary clear space, he should assume that there is a car just out of sight and approaching at 60 mi/hr. This is the basis for rules about passing on a hill or on a turn.

Figure 8 shows the conditions under which one may pass slower cars without exceeding 40 mi/hr. Curve *A* shows the times and corresponding distances required when the passing car maintains its speed of 40 mi/hr. Curve *B* indicates the necessary times and distances when one must first slow down to the speed of the slower car before attempting to pass it. In order to make it easier to estimate the various distances one may translate the latter into numbers of telephone poles visible within the clear space ahead. Telephone poles on the highways are usually spaced about 150 ft apart, although in cold climates they may be closer, owing to the weight of sleet the wires may have to support. Various tests have shown that most people can judge from a single glance the number of objects seen, if there are not more than five. Therefore a driver may estimate from a single glance at the telephone poles whether he has as much as 600 or 700 ft free for passing. Sufficient allowance should be made for the nearest pole being less than 150 ft from the driver and also for the parallax which may make at least one of the distant poles appear to be between him and the approaching car, when it is really some distance beyond that car. Since two cars moving 40 and 60 mi/hr approach each other with a speed of 100 mi/hr (147 ft/sec), the num-

ber of seconds required for passing equals the number of telephone poles that must separate the cars if passing can be accomplished without reduction of speed.

Only a few of the more common applications of physics have been discussed here. A much more complete study of driving problems, especially those encountered on wet roads, was published by R. A. Moyer[2] in 1934. There are many special cases, such as those discussed by Chapman,[3] in which a knowledge of fundamental physical principles will help one to decide the best procedure in a given emergency.

[2] Reference 1.

[3] Chapman, "Should one stop or turn in order to avoid an automobile collision?" Am. J. Phys. **10**, 22 (1942).

Three Experiments in Electricity

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THE first of the following experiments deals with electrostatics, the second with direct currents and the last with rectification of alternating current. They are described together because they use, in part, the same apparatus.

GROUP EXPERIMENT IN ELECTROSTATICS

Electrostatics is too often associated with rubber rods and cat's fur, with static machines, Leyden jars and a general atmosphere of impracticability. There are many ways in which such an experiment can go wrong. With contact and induced charges, potential and charge measurements and absolute and relative potential, it is not easy to gather together the results of electroscope observations into a connected whole; the lesson learned is likely to be simply that electrostatics means poking rods at electroscopes and is fortunately unrelated to practical electricity. To make the experiment a real basis for the study of current electricity it should be performed as a closely supervised group experiment,

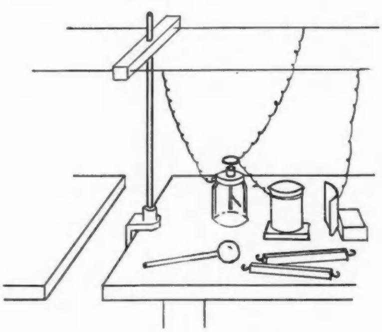

Fig. 1.

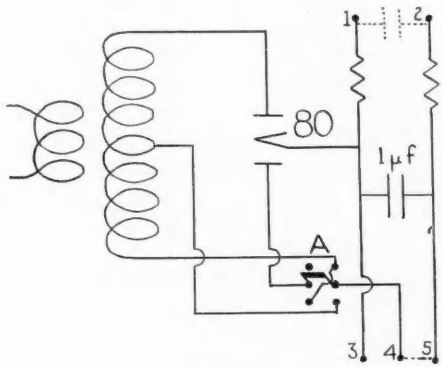

Fig. 2.

the instructor pointing out the significance of each observation and correcting false observations. Moreover, the charges should be obtained from conductors maintained at a constant potential difference rather than from a static machine, preferably using the same wires that will later be used for "practical" experiments.

Arrange several laboratory tables in line and mount along their length a miniature "power line" consisting of two tightly stretched iron wires (Fig. 1) of rather small gauge. The wires are supported and kept about 1 ft apart by wooden sticks mounted on iron rods at intervals. A simple power pack is arranged to give a potential difference of 300 to 500 v for an average electroscope deflection or 600 to 1000 v for a larger deflection. For the purposes of laboratory discussion the potential differences will be considered as 1 and 2 statvolts, respectively. Each line from the power source is blocked with a 1-megohm resistor.

The power-pack circuit is shown in Fig. 2. A Thordarson transformer T13R01 (350-0-350 v) is used. Terminals *4* and *5* are strapped together. With the switch *A* thrown upward it gives about 1000-v peak and with the switch down, 500 v. These voltages give convenient deflections. The upper terminals, *1* and *2*, which are protected by resistors, are used in this experiment. When it is desired to give a slight shock, a 0.005-μf condenser is placed across the terminals (unprotected by resistors), as shown by the broken lines.

The electroscope used should be easily visible. It can be made from a wide-mouthed glass bottle with a metal cap. A hole is punched in the cap for a rubber stopper and the stem mounted in the latter. A single aluminum leaf lying along the stem should be used. The upper end of the stem supports a small metal plate with a hole near the edge for hooking in a wire. A small wire loop is soldered to the bottle cap to hold the grounding wire, and a strip of metal foil is glued down each side of the bottle to distribute the ground potential from the metal top to the interior walls. If the electroscope is to be used in humid weather, sealing wax or Lucite should be substituted for the rubber insulator.

The students perform the experiment at the different tables under the direction of the instructor. We observe that one wire is grounded. The other wire is charged; we can get a slight shock from it. We now connect the electroscope case to the grounded wire and learn how to charge the stem by induction from a rubber rod and how to test the sign of a charge. Then, on an insulated ball we carry charges from the charged wire and test their sign. Tucking our feet up off the floor, we can substitute our bodies for the ball; evidently our capacitance is the larger since we can do in one trip what the ball does in many. We connect the electroscope across the line; this shows that it is essentially a voltmeter. It indicates the potential difference; reverse the connections and it reads as before, though the stem is now connected to ground. Observe this strange effect: we connect a calorimeter cup to the charged wire; no charge can be carried from the interior; but connect the wire from interior to electroscope and the latter reads full voltage. This is a great puzzler and is very instructive; be sure to distinguish potential difference and charge. After discussing the meaning of potential difference, we change the line voltage from 1 to 2 statvolts, observe the deflection and so roughly calibrate our voltmeter. If the ball has a radius of 1 cm, it has unit capacitance and, when touched to the 2-statvolt wire, gets a 2-statcoulomb charge. Let us see how many such charges are required to raise the potential of the electroscope to 1 statvolt; thus we find the capacitance of the electroscope.[1]

Connect the electroscope to a calorimeter cup, placed on a block of paraffin for insulation, and observe its capacitance; note that the capacitance increases still more when a grounded plate is made to approach the cup (Fig. 1). Now, using all this capacitance to slow things a bit, one may find out how long it takes a charge to leak onto the electroscope through some wooden sticks.[2] Since we know the capacitance, we now have the current; knowing the voltage, we find the resistance of the sticks. (Since the potential difference used is 2 statvolts and the electroscope is raised to 1 statvolt, we have a mean potential difference of 1.5 statvolts; but in this preliminary experiment we neglect this change in voltage.) Finally, the sticks are collected from the class, are hooked in series across the line and the result discussed; indeed, this discussion may be confirmed by measuring the potential difference across each stick with the electroscope.

Evidently this experiment furnishes a broad background for the whole subject of electric currents. The concepts of potential, charge, capacitance, current and resistance are introduced and each quantity roughly measured. In a subsequent experiment the current-voltage-resistance relations are again investigated, this time with 110-v d.c. substituted on the line for the power pack, lamps for the sticks, and electromagnetic ammeters and voltmeters for the electroscopes.

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[1] Of course, the ball does not give up all its charge to the electroscope. If one wishes to meet this objection he performs the experiment with the cup on top of the electroscope, placing the charges on the interior. Then show that (surprisingly) the capacitance is larger when this same cup is placed some distance away and connected to the electroscope by a wire.

[2] The sticks are common wood about the size of a lead pencil with a hook screwed in either end. If soaked in a salt solution, washed and dried they will retain indefinitely a suitable conductivity for use in periods of low humidity. In summer, glass rods with wire twisted around their ends for contact serve better.

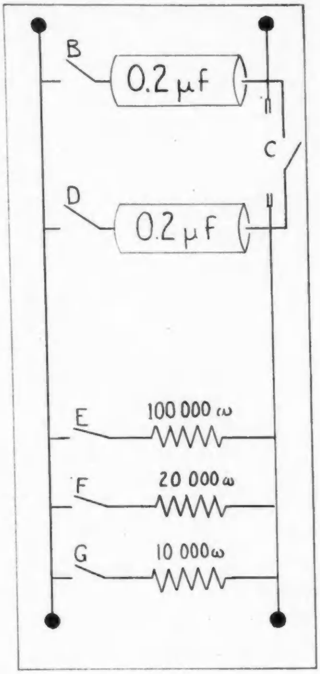

Fig. 3.

LINE DROP IN A POWER LINE

The iron wires shown in Fig. 1 may be used to represent a power line. At one end they are connected to a 110-v d.c. source, and lamps are connected across the line with Fahnstock connectors at 2-m intervals. An ammeter is connected in series with each lamp. With his own voltmeter the student finds the potential drop across each lamp and the line drop. He observes the lamp currents and makes a diagram showing the current in each part of the circuit as well as all potential differences. He may then be asked to compute the resistance or the resistivity of the wire or to compare the power consumption with the rating for each lamp.

DEMONSTRATION OF RECTIFICATION AND FILTER CIRCUIT

The apparatus represented in Fig. 2 is convenient for demonstrating on the oscilloscope full-wave and half-wave rectification. A plug is made from the base of a burned-out radio tube (strapping a plate and a filament terminal together) which can replace the 80 tube to pass the alternating current from the transformer. On a board (Fig. 3) are clearly arranged the filter elements and load resistances which will be used to illustrate the principle of filters.

The strap between terminals *4* and *5* (Fig. 2) is removed, and *3* and *4* are connected to the upper terminals of the filter board (Fig. 3). The lower terminals of the filter board are connected to the oscilloscope. The demonstration begins with the shorting plug substituted for the tube, switch *A* up, *C* and *F* closed and the other switches open. The oscilloscope now shows the alternating current from the transformer. The rectifying tube is now replaced, and the oscilloscope shows the simplest type of rectification—half-wave rectification—with all negative voltages eliminated. Switch *A* is now thrown down and full-wave rectification is shown, with negative voltages reversed.

Each of these pulsating currents can now be filtered. Closing switch *B* or *D*, we show the partially filtered output; it still has a strong ripple, particularly with half-wave rectification. This is because we are drawing a load. If switch *E* is closed, instead of *F*, the rectification is very good. With the largest load—*G* closed—the condensers are of little use.

Now contrast the effect of a choke. A 20-h choke is mounted on a small Bakelite plate and provided with knife terminals so that it can be inserted in place of the switch *C*. With the condenser switches open we find that the choke filters best with large loads. Introducing the condensers again, we have a common filter circuit that filters for the whole range of loads—not perfectly because we are using rather small condensers for the demonstration of the ripple.

It is of course quite easy to explain these effects —why the condenser is ineffective for large currents and the coil for small—and the visual demonstration is very satisfactory.

In order to keep the base line of the curves in the center of the oscilloscope screen, the connections should be made directly to the plates of the oscilloscope tube, with a grid-leak potential divider to reduce the voltage to an appropriate value, and not through the auxiliary oscilloscope circuit which automatically centers the whole figure.

A Demonstration of Radio Fundamentals and Speech Quality

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FOR several years the *American Journal of Physics* has offered new "kinks" and subject matter contributions relative to radio. By combining some of these suggestions with materials gleaned from other sources, and adding some of his own ideas, the writer has developed an easily performed demonstration that shows some of the fundamentals of radio, and which, in addition, brings to the attention of the student the physical basis of quality in speech, a topic that is usually neglected in the general physics course.

In teaching beginners the ideas of radio communication one must deal with radiofrequency, audiofrequency and detection. By modifying the methods of Trotter[1] one can easily demonstrate these factors.

The entire set-up for the demonstration is shown in Fig. 1. The amplifier and the record

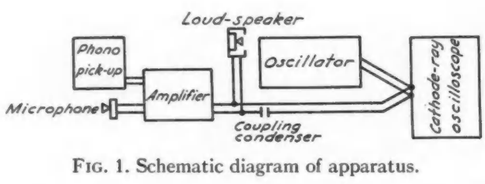

FIG. 1. Schematic diagram of apparatus.

player in this case were built by students under the supervision of the writer; the other equipment needed is now usually standard in most physics laboratories. One of the essential components of the assembly is the 0.5-μf condenser which must be used in coupling the amplifier to the cathode-ray oscilloscope. This condenser keeps the beat-frequency oscillator from feeding too much of its energy into the low impedance coil of the loudspeaker.

In the reception of radio the electromagnetic wave that carries the speech or music is a fundamental factor which is difficult to explain with an ordinary radio set. One may approach such an explanation by letting a 5000-cycle/sec wave represent the carrier wave. The student is impressed with the existence of this carrier wave because he can hear the effects of it through the loudspeaker. For demonstration purposes the oscilloscope can be adjusted to give a stationary picture of this wave with a suitable amplitude. This demonstrates the first stages of the usual radio receiver, and one can illustrate the amplification of these first stages by increasing the amplitude of the wave with the volume control of the oscillator.

To illustrate the audiofrequency form one may use a record cut with ordinary standard frequencies such as 256 and 512 cycle/sec. These are impressed upon the oscilloscope through the amplifier, with the beat-frequency oscillator shut off. It is well to have a wave form that is stationary with the same setting of the sweep circuit which was used with the assumed radiofrequency, or the latter frequency can be adjusted to the same setting. Here again the amplification of the audiofrequency stages of a radio receiver can be demonstrated by increasing the amplitude of the audiofrequency wave by means of the volume control on the amplifier.

The two waves—carrier-frequency and audiofrequency—can now be combined to show modulation by turning on the beat-frequency oscillator. The volume of the oscillator should be turned up and the amplifier volume control adjusted so that a modulation of approximately 50 percent is secured. The student can easily compare the pattern seen on the oscilloscope screen with the diagrams in his textbook. Manipulation of the volume control of the amplifier will easily show the effect of varying the percentage of modulation and of overmodulation.

To illustrate detection the zero-axis control can be used to lower the pattern on the oscilloscope screen so that only the upper half of the wave is shown. The screen now shows the assumed carrier wave and its envelope created by the audiofrequency. The beat-frequency oscillator can be turned off, whereupon only the envelope and detected portion of the audiofrequency wave remains on the screen.

The action of the volume control used in a radio receiver has been illustrated through the

[1] Trotter, Am. J. Phys. 7, 411 (1939).

several manipulations involved in the previous steps. To demonstrate "tone control" one may play a record of band or orchestra music and, with the aid of a filter, cut out the higher frequencies; the visual pattern on the screen becomes much simpler as the low tones are brought into prominence by the absence of the high tones. In his own demonstration the writer has a tone control on both a tuned radiofrequency receiver and the amplifier, which makes the effects much more pronounced. In a few words one can easily explain that the tone control is simply a bypassing series device consisting of a variable resistor and a condenser connected into the audiofrequency stage of the radio set, or, as in the present case, of the amplifier, in either the plate or the grid circuits.

The second part of the demonstration, which deals with certain speech qualities, has proved of value to both the physics and speech students to whom it has been shown. Most textbooks of physics do not deal with the fundamental frequencies involved in speech and intelligibility or with the energy content of the vowels and consonants. The cathode-ray oscilloscope furnishes an excellent opportunity to bring these factors to the students' attention.

Using the microphone one may show on the screen the relatively simple wave forms of the vowels in either long or short accent and point out that the energy content continues for the duration of the sound. This behavior can be contrasted with that of the consonants, where the wave takes a decided jump at the beginning of the letter and then quickly dies. This part of the demonstration is of particular value to students of speech, for it shows them the reasons for the irritating characteristics of many speakers, who have a tendency toward using *ahhh* or *uh*, or hissing certain consonants.

Demonstrations of characteristics such as the umlauted vowels of German, nasalness of French, irregularities of English or smoothness of Chinese, lip or throat qualities, also appear to be enlightening. The writer has had German, French, Dutch, Chinese and Japanese students demonstrate the qualities of their languages, and of the several, Chinese has the most regular and velvety nature.

The fact that the intelligibility of speech is dependent on a few basic frequencies for each speech sound can be illustrated by means of the sweep circuit and tone control. By speaking different vowels into the microphone one may show that each sound has these characteristics, while the tone control will show that if frequencies of 500 cycle/sec or more are cut off, the speech is no longer intelligible.

One may also illustrate the Resonoscope,[2] a device that is finding increased usage by musical instrument manufacturers and by music schools in testing and training the tone characteristics of the human voice. The stationary pattern corresponding to that of a standard tuning fork may be formed by means of the sweep circuit. If a tone that is slightly "off key" from this standard frequency is sung into the microphone, its pattern will move to the right or left on the screen, depending upon whether it is higher or lower in pitch than the true tone, and the rate of movement in either direction indicates the degree of sharpness or flatness of the tone. The degree of smoothness of the wave form indicates the quality, or timbre, of the note. The more irregularities, the more overtones are present.

I wish to acknowledge my indebtedness to several of my former students who have aided in this demonstration and its organization.

[2] Allen B. DuMont Laboratories.

THERE are those who maintain that the interpretation of science is a function of philosophy or history or both, rather than of science itself. This has been extensively tried, however, and found wanting, partly on account of lack of an adequate knowledge of science on the part of philosophers and historians. Let those men of science who would delegate this responsibility try to single out from among their nonscientific colleagues those to whom it could safely be entrusted. The result will make it clear that the interpretive responsibility must be discharged by the scientists themselves if it is to have any chance of being done acceptably.—L. W. TAYLOR, *Physics: the pioneer science*, p. viii.

NOTES AND DISCUSSION

An Aid in Showing Mitscherlich's Experiment*

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THE famous experiment of Mitscherlich which demonstrated the change of the angle between the optic axes of a biaxial crystal—for example, selenite—with change in temperature is of unusual interest to students of optics and is, as R. W. Wood[1] has said, "one of the most beautiful lantern demonstrations ever devised." Yet it is one that is shown in few laboratories, and most of those are associated with geology departments.

Some years ago, the addition of an accessory to the more or less conventional apparatus for projecting the interference figures formed by converging polarized light made this demonstration simple and readily available. In place of the usual holder for the slab of crystal, there is set a heater, a section of which is shown in Fig. 1. The main part is simply milled from a metal block and then covered. The longitudinal tubes permit the passage of a stream of heated air through the chamber. The transverse tube allows the converging beam of light to enter the slab of crystal which is laid upon the thin metal cover. A layer of insulating material and a clamp complete the assembly for the crystal holder.

We have used for a heater a Bunsen burner under a brass tube connected to the low pressure air line, but the temperature control is not as satisfactory as with an electric heating unit within the air line. The adjustment of the heating rate needs some attention, as it is desirable not to have the temperature rise too rapidly, and again one must be careful not to overheat the crystal. The transition temperatures are quite definite; thus selenite is uniaxial at 91°C and is permanently changed at about 128°C.

The similar experiment of change of angle of axes with change in frequency seems, again, to be better known to mineralogists than to physicists. However, it can be shown with even less trouble than the Mitscherlich experiment, provided there is at hand a slab of a suitable crystal.

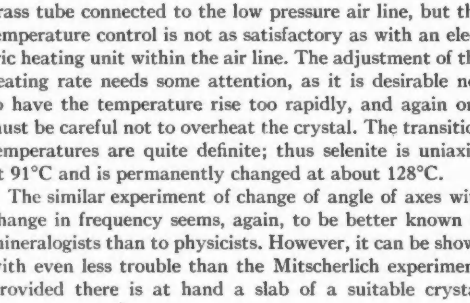

FIG. 1. Section of heater.

Brookite appears to be the most satisfactory, though a good specimen is very rare. For this demonstration we do not try to project the pattern but use a vertical apparatus, the illumination for which is reflected from a 45° mirror upon which is projected the spectrum. The illuminating beam can be slowly rotated by means of a slow motion rotating head, so that the student can look down at the figure and change the frequency of the light reaching his eye by means of a convenient hand wheel.

* Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.

[1] *Physical optics* (ed. 3), p. 386.

Physics and Bicycles

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A BICYCLE provides a number of interesting examples of well-known mechanical principles. Several illustrations of this fact are brought together in the answers to the following questions.

Question 1. A man standing beside a bicycle is holding it erect without touching the handle bars. If he tips the bicycle to one side, why do the handle bars turn?

The front assembly—wheel, fork, handle bars—turns about an axis that is not vertical but meets the ground just ahead of the lowest point of the front wheel. The ground pushes upward on the lowest point of the wheel. When the bicycle is not vertical this upward force has a component that exerts a torque about the axis of the front assembly. If the bicycle is tipped to the right [left] the vector that represents the torque points downward [upward] along the axis, and the handle bars swing to the right [left].

Question 2. Why is it possible for a man who walks beside a bicycle to guide it without touching the handle bars?

Suppose that he wishes the bicycle to turn to the right. If he tips it to the right the torque mentioned under Question 1 swings the handle bars and turns the bicycle in the desired direction. There is also a small torque in the same direction because of the gyroscopic tendency of the front wheel to turn its axis of spin toward the axis of the torque that is brought into play as the bicycle tips.

Question 3. Why does a riderless bicycle tip over sooner when it is left at rest without lateral support than when it is sent running along a road?

When the bicycle is running along the road the torques mentioned under Question 2 turn the handle bars whenever the bicycle begins to tip. In accord with Newton's first law of motion the bicycle tends to go straight ahead. But the front wheel is forcing it to follow a curve, and the requisite centripetal force is supplied by friction at the ground. If we make use of D'Alembert's principle and imagine a reversed effective force applied at the center of mass, we may then treat the problem as if it were one in statics. The friction and the reversed effective force constitute a couple that opposes the tendency to tip over.

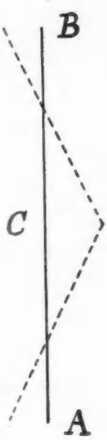

FIG. 1.

Question 4. When a man walks beside a bicycle and pushes it along without touching the handle bars, why is it easier to guide the bicycle when he pushes it forward than when he pushes it backward?

As already mentioned, the axis of the front assembly meets the ground just ahead of the bottom of the front wheel. When the bicycle is moving forward and turns toward the right, the bottom of the front wheel trails a little to the left. The backward friction at the ground and the forward push on the front assembly consitute a couple which can be represented by a vector that points vertically upward. This vector may be resolved into a small component along a line perpendicular to the axis of the front assembly and a larger component upward along that axis. The latter urges the wheel back toward the straight-ahead position. The caster given to the king pins of automobiles acts in the same way and makes the car easier to steer. When the bicycle is moving backward the couple is reversed and tends to increase any deviation of the wheel from the straight-ahead position.

Question 5. Why is it possible for a man to guide a bicycle when he rides without touching the handle bars?

If he can shift the center of mass of himself and the bicycle to one side, the two torques mentioned under Question 2 will make the path curve. But how can internal forces provide the angular momentum that is involved in swinging the center of mass to one side? The answer is that they do not. The force that displaces the center of mass is an external one.

The guiding of the bicycle seems to be brought about as follows. Let the man and bicycle be represented by the full line AB in Fig. 1, where we are looking at them from behind, and let their center of mass be at C. Suppose that the man wishes to turn to the right. The position of the center of mass is not affected by internal torques; and if there were no unbalanced external force, internal torques brought into play by leaning slightly to the left or by trying to push the seat of the bicycle to the right might cause the man and bicycle to take the position suggested by the dotted lines. This is prevented by a frictional impulse at the ground, an impulse that acts toward the right and prevents the wheels from slipping to the left. It is well known that an external impulse always imparts velocity to the center of mass of the system on which it acts, whether or not the line of action of the impulse passes through that center of mass. In the present case the center of mass moves to the right, as may be seen in the customary way by imagining two impulses of equal magnitude and opposite sense applied at the center of mass and parallel to the frictional impulse at the ground. When the center of mass is no longer in the vertical plane through the bottoms of the wheels a gravity couple comes into play and tips the bicycle farther to the right. The rider can now straighten up on the bicycle and lean inward with it.

High School Physics and the War

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IN 1890 the U. S. Office of Education made its first study of courses offered in American high schools. Since then, continuing studies have been made, annually until 1906 and afterward at intervals of several years until 1933–34, when the last such study was completed. There were nine subjects offered in 1890, of which physics was one; by 1933 this number had increased to more than 200.

This large increase in the number of offerings was accompanied by an equally striking growth in the number of students enrolled in high schools. The population of the nation in 1890 was 62,900,000 and the high school enrolment was 202,000—0.3 percent of the total population and 3.8 percent of the children of high school age. In 1940 the population was 131,670,000 of whom 6,600,000 were in high school—5 percent of the population and 68 percent of those of high school age. Thus, while the general population was increasing 209 percent, the number of children of high school age—14 to 17 years—increased 181 percent and the high school enrolment increased 1700 percent.

Of the students who graduate from high school, only about 20 percent go on to college; for the rest, high school provides their terminating formal school experience. It is for this reason that the schools have attempted to offer the subjects that were wanted to meet both vocational and cultural needs. Not until the entrance of the country into the war last December were high school youth as a class urged to register for specific subjects. Now, with selective service operating, with the draft age already lowered to 20 years and discussion of further reduction, youth very properly want to be counselled. They have a right to demand that they be told how to adjust their plans so that they may be better prepared to serve their country.

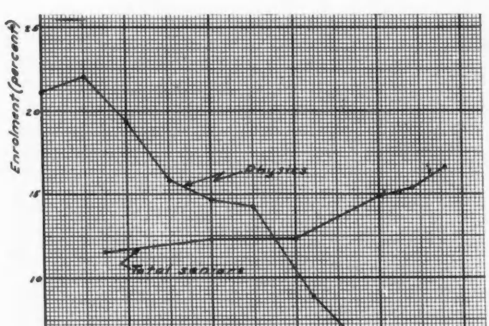

FIG. 1. Total numbers of high school seniors and total enrolments in high school physics, by years.

The armed services are not only asking that all prospective soldiers and sailors be physically conditioned; they are also advising all high school youth capable of carrying additional mathematics or physics to do so. The Navy urges all who can to include trigonometry. There are, of course, plenty of sound reasons for such counsel. Those arguments need not be given to those who know the answers.

Germany recognized the need for these subjects long ago. Shortly after Hitler's rise to power the schools of Germany started giving greater and greater emphasis to practical physics. The movement went nearly unnoticed, for a totalitarian state can act and explain later. We, on the other hand, are having to convince each of the many thousands of school boards and school administrators that they should make available courses in physics and mathematics and should urge all competent boys and girls to register for these subjects.

Only 47 percent of our high schools have been offering physics and the number of pupils registering for this science has been a decreasing proportion of the total enrolment. The accompanying graph (Fig. 1) gives little comfort. It does make clear that the job there is to do is one that will require near missionary zeal.

The fact that physics has not been offered in more than half of our high schools makes compliance with the wartime request of the armed services more difficult. A further problem is that, in the high schools where physics has been offered, only a small proportion of the eligible pupils have taken the subject. An immediate increase in enrolment in physics in those high schools where it is offered will create an instructional shortage. Add to this lack the necessity of supplying teachers to those high schools that need to offer physics and the acuteness of the teacher problem is evident. The supply, because of the war, is less than normal at a time when the need is greatest. It will be in the towns and rural areas where the teacher shortage will be greatest, because of poorer salaries and less security. Most cities report through their personnel directors that their teacher supply is more nearly adequate.

The U. S. Office of Education, through its ESMWT program, is making available through more than 200 eligible institutions refresher and supplementary teacher-training subject-matter courses in physics and mathematics. Many high schools under pressure of war need will find these ESMWT courses of great assistance in giving training in service to their emergency teachers of these critical subjects. Teachers joining for the emergency, and regular teachers of less emphasized subjects accepting assignment in the emphasized fields, are the types the ESMWT courses should serve.

The number of high school pupils taking physics should more and more nearly approach 100 percent of those capable of handling the subject. The need is very great and will not wait. It is now, each day, each month, this fall, this year that those who are capable of appreciating the situation must work and continue to work, to encourage schools to offer and capable pupils to take physics. It is now and from now on that each and every skilled physicist must give aid and counsel in this problem which hinges on teachers, and every assistance to make those teachers more able. The ESMWT courses in physics and mathematics for teachers fill a distinct need which high school teachers of physics should utilize.

Ernest Calvin Bryant, 1867-1942

PROFESSOR EMERITUS ERNEST CALVIN BRYANT, former head of the department of physics at Middlebury College, died at Middlebury, Vermont, on September 7, 1942, after a brief illness.

Professor Bryant was born at Manchester, New Hampshire, in 1867. His undergraduate work was done at Middlebury College, from which institution he held a B.S. degree. He attended the Massachusetts Institute of Technology, and received a S.B. degree in 1893. He also studied at Cambridge University during two sabbatical leaves, in 1913–14 and 1926–27. During his first term at Cambridge he conducted research under Sir J. J. Thomson. In 1895 he came to Middlebury as Professor of Mathematics and Physics and in 1912 became Professor of Physics, founding the department at Middlebury.

He was a member of the Middlebury faculty for 42 years, until his retirement in 1937. He kept his interest in physics to the very end and, while teaching, was noted for his brilliant lectures and demonstrations in general physics. For many years he was voted "Middlebury's most valuable teacher."

His ability and knowledge in astronomy were well recognized. He served as a research assistant at the Yerkes Observatory in 1921, was a member of the Catalina Island Eclipse expedition in 1923, and in 1927 accompanied the Cambridge University Eclipse expedition to Norway. In August 1932, at the age of 65, he made observations of the solar eclipse at Freyberg, Maine, from an airplane at 15,000 ft.

Professor Bryant served longer than has any other member of Middlebury's teaching staff. His wide experience and sound judgment were always sought, and he gave freely of his time and energy to both students and faculty. He was loyal, possessed great personal charm, and his sympathetic nature gained for him a host of friends. It is with sincere regret that we record his passing.

BENJAMIN F. WISSLER

DIGEST OF PERIODICAL LITERATURE

Preservation of Historic Apparatus

The Council of the Newcomen Society (England) directs attention to the need for watchfulness in the preservation, not only of valuable scientific documents, but of objects of enduring scientific interest. An irreparable loss to Manchester was Robert's slide lathe of 1820 which was scrapped because "The lathe was very large and not complete [this was incorrect] and was seriously obstructing our work." A more recent attempt to scrap the contents of Wortley Iron Works near Sheffield, particularly two unique eighteenth-century tilt hammers, has fortunately been averted by prompt action. Such dangers of destruction are greatest when the salvagers are enthusiastic but ill-informed persons.—E. L. BURNE AND H. W. DICKINSON, *Nature* **150**, 181 (1942). D. R.

Education but Not Educationalism

We have the most elaborate and expensive educational system in the world, and perhaps in proportion to the machinery, the most ineffectual—ineffectual, or worse, because it is more or less completely controlled by the well-organized army of education professors and their offspring and allies. Their sociological, psychological, and generally progressive and cheaply utilitarian notions have steadily undermined old ideals of intellectual discipline and solidity of subject matter. It is only through the recapture of the humanistic tradition of pedagogy that we can combat the specious attractions of the educationists' gold bricks and train the next generation so that, in Miltonic language, "they may not, in a dangerous fit of the commonwealth, be such poor, shaken, uncertain reeds, of such a tottering conscience, as many of our late counsellors have lately shown themselves, but steadfast pillars of the state."—D. BUSH, ΦBK *Key Reporter* **7**, No. 4, 1 (1942). D. R.

Joseph Henry and Space Communication

When Joseph Henry resigned his professorship of natural philosophy at Princeton to assume the administration of the newly established Smithsonian Institute at Washington, he said, "If I go, I shall probably exchange permanent fame for transient reputation." In this prediction he was so far right that for many years the important contributions which he made to the science of electromagnetism were largely overlooked and he was esteemed rather as the wise and learned Secretary of the Smithsonian than as a productive investigator of high order.

At the time of Faraday's discovery of the induced current, Henry was teaching at the Albany Academy. There he brought the electromagnet to its present form and distinguished two types—the "quantity" magnet, which was wound with a comparatively small number of turns of coarse wire, and the "intensity" magnet, which had many turns of relatively fine wire. He used the intensity magnet in a circuit containing a mile of wire and rang a bell by sending a current through the circuit. His inventions and discoveries cover the essential features of the electromagnetic telegraph.

Henry's daughter writes that her father observed the induced current as early as 1830. She quotes Henry's friend, Doctor Cuyler, as saying: "Your father often spoke to me of his disappointment about the discovery. 'I ought to have published earlier,' he used to say, '. . . but I had so little time. It was so hard to get things done. I desired to get out my results in good form, and how could I know that another on the other side of the Atlantic was busy with the same thing.' " It seems probable that Henry really was ahead of Faraday in the observation of the induced current, and that he failed to establish his claim to the discovery because of a desire to show his results on a larger scale. If he had published at once, his fame would have jumped the Atlantic. As it was he was little known outside of this country.

Going to Princeton in November 1832, Henry spent the early years of his professorship there in developing his courses and installing much needed apparatus. He constructed the great magnet which is now in the museum of the Palmer Physical Laboratory; he set up a complete telegraph line between his house and the laboratory. The one original research in those years was the development of the observation reported by him in his paper of 1832 of what used to be called the "extra current"—the momentary increased current that occurs in a circuit when it is broken.

In 1837, Henry was given leave of absence from Princeton, on full salary, and spent the year abroad where he made the acquaintance of many leading English and French scientists. On his return he settled to a definite field in which he made his most important discoveries, and worked in that field until he went to the Smithsonian Institution.

He thought that most of the work on electromagnetic induction had been concerned with the relations between the current and the magnetic field, and that no one had properly developed what he called "the purely electrical part of Dr. Faraday's admirable discovery." For work in this field he used "coils" of insulated copper ribbon; "helices" of insulated wire; a "magnetic spiral," a spiral of wire wound tightly around a small cylinder in the axis of which a sewing needle could be placed; a low resistance electromagnet; and other accessory apparatus. He first investigated the currents of self-inductance and showed that the coils gave a quantity current; the long helices, an intensity current. Turning next to the ordinary Faraday current, he showed the conditions in which they would be either quantity or intensity currents. By combining the coils or helices, he used the secondary current to induce a tertiary current, and further currents up to those of the fifth order. He then tried the effect of the discharge of "ordinary electricity" from the Leyden jar for the primary circuit and found that there resulted a current in the secondary. Anomalies in the direction of the current indicated by the magnetization of the needle in the

magnetizing spiral led him to the discovery that the discharge is not in one direction only but is oscillatory in character.

While on this part of his investigations Henry found that the effect of the discharge in the primary could be observed in a distant secondary, and he transmitted the effect from his telegraph line to a parallel wire 220 ft away "with the bulk of Nassau Hall intervening." Although he certainly did not realize that this achievement was the forerunner of one of the most extensive applications of electricity in modern life, he did recognize its theoretical implications. Referring to these experiments in a lecture given before the American Association for the Advancement of Science, in 1851, he said, "As these are the results of currents in alternate directions, they must produce in surrounding space a series of plus and minus motions analogous to if not identical with undulations."

The great work which Henry did while at Princeton he presented in a few memoirs to the American Philosophical Society, which at that time was a local organization of little importance, and they appeared in its *Transactions* two or three years after their presentation. It is not likely that they were even properly brought to the attention of European workers in the field; certainly Faraday when he studied the "induction of a current on itself" was unaware that Henry had already announced the discovery of the same effect. Perhaps only now—a century after Joseph Henry's first announcement in June, 1842 of his space transmission experiments—is the scientific world coming to recognize the importance of his pioneering activities in the modern field of radio transmission.—W. F. MAGIE, *Proc. I. R. E.* **30**, 261–266 (1942).

D. H. D. R.

Lantern Slides of Crystals

A clean lantern-slide cover glass is immersed in a saturated solution of the compound whose crystals are desired, and the solution is allowed to evaporate very slowly. A suitable container is a glass pie plate covered with another similar plate. The rate of evaporation can be controlled by means of a thin wedge beneath one side of the cover. The growth of the crystals is allowed to continue until a sufficient deposit has been accumulated; the best time to remove the cover glass can only be learned by experience. The glass is set vertically to drain away the solution and the remainder quickly evaporates. Drops of Duco or similar cement are put at the corners of the glass and allowed to set so as to support a second glass slide that just touches but does not rest upon the crystals. The edges are bound with black tape, and the result is a slide that fits the slide-holder of an ordinary lantern.

No rule can be given for the best depth of solution above the glass slide on which the crystals form. In some cases the glass should be barely covered; in others it should be at a depth of 5 mm or more. Compounds whose saturated solutions are rather dilute were found to yield the best results. Such compounds as potassium ferricyanide, mercuric chloride and oxalic acid are very suitable. Cupric sulfate, although it forms bulky crystals, can nevertheless be made to give good results.—HARRIETT H. FILLINGER, *J. Chem. Ed.* **19**, 369–371 (1942).

J. D. E.

Check List of Periodical Literature

Radiation pattern of the human voice. D. W. Farnsworth, *Sci. Mo.* **55**, 139–143 (1942). A brief account of recent pioneer work on the directional characteristic of speech as it is affected by the shape of the mouth, head and body.

Present state of the theory of stellar evolution. H. N. Russell, *Sci. Mo.* **55**, 233–238 (1942). The central problem of stellar evolution lies in physics and is this: given a large quantity of matter of known mass and atomic number, isolated in space; to find its configurations of equilibrium and its steady states of slow secular change. The sequence of these changes defines the evolution of the stars.

Recent advances in our knowledge of the photographic process. C. E. K. Mees, *Sci. Mo.* **55**, 293–300 (1942). The direction of recent advances is (i) in the elucidation of the structure of the light-sensitive materials and the factors that produce great sensitivity in the silver bromide crystals, (ii) in the study of the action of light itself and of the change that occurs in the exposed crystals and (iii) in the study of the development reaction.

Social nature of science. L. G. Brown, *Sci. Mo.* **55**, 361–368 (1942). After the War there will be many demands for a "tribal" scapegoat in which all blame can be centered, and science with its dominant role in this war will not be overlooked. The already strong and rapidly spreading belief that wars would be ended if science could be curbed is based on a misconception of the true social nature of science. Only if this true social nature is recognized by every one concerned will it be possible to save science after the War.

System of photometric concepts. P. Moon, *J. Opt. Soc. Am.* **32**, 348–362 (1942). This proposed, comprehensive system of concepts, names and units associated with the geometric relations of radiometry and photometry is of such character that it need not be accepted or rejected in its entirety; thus the writer of a book or a paper may adopt such parts as he feels are desirable.

Protection of eyes against light from incendiary bombs. Anon., *Bur. Stand. Tech. News Bull.* No. 300 (1942). Blue-green, sage green or greenish-yellow glasses of shades 2.5 to 3 (transmission, 23 and 14 percent, respectively) will prevent blurring of vision by the intense light from a burning bomb. Shade 4 is better but seems too dark for safe movement around a darkened room or roof. The light-colored blue, pink, amethyst, reddish-brown and other nondescript colored glasses sold for sportswear are not generally to be recommended for prevention of "glare."

Mass spectrometry. E. B. Jordan, L. B. Young, N. D. Coggeshall, J. A. Hipple, D. Rittenberg, *J. App. Phys.* **13**, 525–569 (1942). Five articles on the history of isotopes, measurement of their relative abundance with the mass spectrometer, gas analysis with the mass spectrometer, and some chemical applications of mass spectrometric analysis.

Author Index to Volume 10

In this index are listed the names of the authors and the titles of their articles. Abstracts of papers read at meetings and of articles that appeared in the "Digest of Periodical Literature" section of the journal are not listed; they are indexed in the Analytic Subject Index.

Analytic Subject Index to Volume 10

The titles of articles are disregarded, the entries being based on analyses of the contents of the original articles. Entries marked (D) refer to digests appearing under "Digests of Periodical Literature" and to abstracts of papers read at meetings; entries marked (R) refer to reviews appearing under "Recent Publications and Teaching Aids."

To facilitate reference to any desired subject, the index is divided into sections arranged alphabetically. The titles of these sections and of various cross-references to them are as follows: